AD-A049 279 HUGHES AIRCRAFT CO FULLERTON CALIF GROUND SYSTEMS GROUP F/G 14/2
HIGH RESOLUTION, HIGH BRIGHTNESS COLOR TELEVISION PROJECTOR: AN--ETC(U)
SEP 77 P C BARON, E R CHARLES, D E SPROTBERY F33615-76-C-0040

UNCLASSIFIED AFHRL-TR-77-33(1) NL

1 OF 2
AD
A049 279

279

AFHRL-TR-77-33(I)

AIR FORCE

HUMAN RESOURCES

AD A049279

AD No.
DDC FILE COPY

HIGH RESOLUT
COLOR TEL

ANALYSIS, IN
PERFORMANCE

D.
D.
Hughe
Grou
Fullert

ADVANCE
Wright-Patterson

Se
Final Report for F

Approved for publi

LABO

AIR FORCE SYST
BROOKS AIR FORC

NOTICE

When U.S. Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise, as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This final report was submitted by Hughes Aircraft Company, Ground Systems Group, Fullerton, California 92633, under contract F33615-76-C-0040, project 6114, with Advanced Systems Division, Air Force Human Resources Laboratory (AFSC), Wright-Patterson Air Force Base, Ohio 45433. Mr. Noel F. Schwartz, Simulation Techniques Branch, was the contract monitor.

This report has been reviewed and cleared for open publication and/or public release by the appropriate Office of Information (OI) in accordance with AFR 190-17 and DoDD 5230.9. There is no objection to unlimited distribution of this report to the public at large, or by DDC to the National Technical Information Service (NTIS).

This technical report has been reviewed and is approved for publication.

GORDON A. ECKSTRAND, Director
Advanced Systems Division

DAN D. FULGHAM, Colonel, USAF
Commander

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: 18 AFHRL-TR-77-33(I)

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER: 9

4. TITLE (and Subtitle): 6 HIGH RESOLUTION, HIGH BRIGHTNESS COLOR TELEVISION PROJECTOR: ANALYSIS, INVESTIGATIONS, DESIGN, PERFORMANCE OF BASELINE PROJECTOR.

5. TYPE OF REPORT & PERIOD COVERED: Final rept. July 1976 – March 1977

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): 10 P.C. Baron, E.R. Charles, D.E. Sprotbery, D.B. Jorgensen

8. CONTRACT OR GRANT NUMBER(s): 15 F33615-76-C-0040

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Hughes Aircraft Company, Ground Systems Group, Fullerton, California 92633

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 16 62703F 61140524 17 05

11. CONTROLLING OFFICE NAME AND ADDRESS: HQ Air Force Human Resources Laboratory (AFSC), Brooks Air Force Base, Texas 78235

12. REPORT DATE: 11 September 1977

13. NUMBER OF PAGES: 142

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Advanced Systems Division, Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio 45433 12 133p.

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

color television displays/projectors
high brightness displays
liquid crystal light valve
optically mosaicked visual system
wide-field-of-view simulation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study addressed the problem of establishing the feasibility of, and defining, a high performance color television projector to be used in optically mosaicked, computer image generator (CIG) driven wide-field-of-view simulators.

The 12-month study consisted of the following tasks: requirements analysis, survey of technology, component investigations, equipment definition, and generation of final report. In general, these tasks were initiated and completed in chronological order.

The first two tasks established the ground work for the study. Based on verbal briefing, reviewing

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

172 370

4B

Item 20 Continued:

documentation, and a visit to the Advanced Simulator for Pilot Training (ASPT) at Williams AFB, the RFP requirements were interpreted, refined and prioritized. The survey task reviewed the extant state-of-the-art in display technology for techniques which held promise of meeting the RFP requirements. Based on this task, it was concluded that only the liquid crystal light valve (LCLV) technology had a chance to do so; however, its performance needed to be upgraded significantly from the then current state.

A systematic investigation of all components contributing to projector operation was therefore undertaken. The lamp*, illumination system*, polarizing beamsplitter*, dichroics, LCLVs*, CRT*, deflection system, projection lens and screen were all subjected to a systematic test/analysis cycle, and improvements were made as required. Samples were obtained, tested and analyzed; breadboards were built and tested; and detailed studies were conducted. Subcontract studies were let, to investigate the dichroics and the projection lens. The latter was a major effort by Kollmorgen Corp. The design of a high resolution, low distortion lens to project on a curved screen represented a significant technical challenge. These investigations resulted in significant improvements in some areas, and a clarification in others, of component performance.

Based on this data, system tradeoffs were conducted to determine what combination of component performances were required to meet RFP requirements. Tradeoffs were generated relating brightness to color purity/range, light falloff to pilot head motion, and resolution to CRT spot size and projection lens cost. Components were then selected (or specified) to result in an RFP-compliant system which yielded minimum overall risk.

Based on these decisions, the projector was then defined in detail. Hardware descriptions were generated for the electronics, the optics, and the mechanical hardware. Integration of the projector into a multiprojector system was considered, and resulted in the development of system alignment procedures, mosaicking specifications, and central hardware to assist with maintenance.

A detailed analysis of every RFP-specified performance parameter was performed. Projector and system level performance were described, and reliability/maintainability characteristics of both a single projector and a multiprojector system were described.

The study concluded that meeting the RFP requirements using state-of-the-art component technology was technically feasible, and could be implemented with practical, reliable hardware.

Portions containing proprietary and contractor evaluation information are contained in AFHRL-TR-77-33(II), with distribution limited to U.S. Government agencies.

*Much of this work was conducted on concurrent independent R&D (IR&D) funds.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

SECTION 1
INTRODUCTION AND SUMMARY

Preceding Page Blank - Filmed

1. STUDY ADDRESSES PROBLEM OF VITAL INTEREST TO THE AIR FORCE

The development of high performance, multi-mission fighter aircraft places increasing emphasis on effective training of pilots so that they can exploit the full mission potential of the plane. Unfortunately a number of factors (fuel prices, cost of planes) have conspired to make the cost of flying these aircraft extremely expensive. A real need exists therefore to develop a wide-field-of-view, high-resolution, color simulator of adequate brightness which can provide effective multi-mission training. Training in a ground-based simulator provides many features over and above savings in cost: it permits training to program limits and/or to fly against preprogrammed maneuvering targets, to fly a larger number of missions per hour, and to provide training aids such as recording, playback, and freeze-motion capabilities.

The computer image generator (CIG)-driven mosaicked infinity optics (pancake window) approach used in the Advanced Simulator for Pilot Training (ASPT) is by far the best approach to date to meet the required field-of-view and resolution, but this approach has some drawbacks. Extremely large cathode ray tubes (36" in diameter) are required as inputs to the display and these tubes cost over $50,000 each and required a major advancement in the state-of-the-art. In addition, the system is monochrome, and upgrading the CRTs to color is not feasible. Because of the all-glass pancake windows and the world's largest cathode ray tubes, the ASPT visual system weighs over 10,000 pounds.

Thus the broad need for improved simulators can be narrowed down to the reduction in cost and weight of the visual display, and the specific need for a projector which not only provides the brightness and resolution of an ASPT cathode ray tube (CRT), but provides color as well, and has the inherent capability for further improvement in resolution and brightness. The projector should be lightweight, should be capable of operating on a motion platform, and should have high availability to support two shifts/day continuous operation. The conceptual design of such a projector was the basic task addressed in this study.

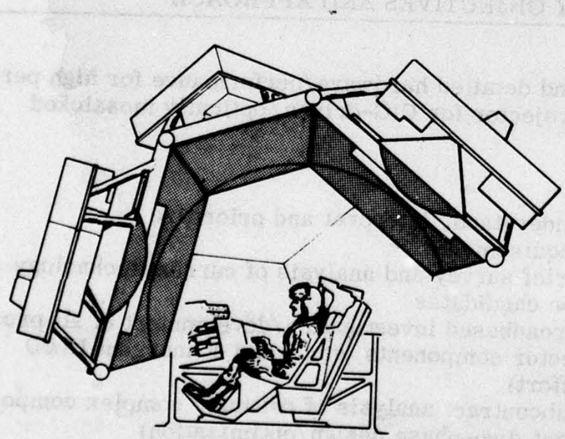


Figure 1. Improved ASPT

TABLE 1. DESIRED IMPROVEMENTS (TO ASPT TYPE DISPLAY)

- COLOR CAPABILITY FOR AIR-TO-GROUND MISSION
- HIGHER BRIGHTNESS AT EQUAL RESOLUTION
- HIGH RELIABILITY AND EASE OF MAINTENANCE FOR HIGH AVAILABILITY
- REDUCED OPERATING COST
- RUGGEDIZED TO TAKE MOTION
- GROWTH TO MULTITARGET CAPABILITY
- REDUCED WEIGHT

2. A SYSTEMATIC APPROACH WAS USED TO DEFINE A RESPONSIVE SYSTEM

To meet the objective stated above meant breaking new ground in the state of the large screen display art. A methodical approach emphasizing quantitative analysis was adopted as the basic approach. It was clear from the start that to reach the performance goals required a complete, element-by-element upgrading of the breadboard HDP-800 single-channel liquid crystal light valve projector. The key feature of the study approach was the comprehensive investigation (jointly funded by the study and independent research and development (IR&D)) of every projector component to determine quantitatively the range of feasible alternatives and potential growth areas for each. A good example of such an investigation was the two-phase subcontract to Kollmorgen to develop a conceptual approach to a required high performance wide angle, long back focal length, curved screen projection lens and then to optimize and analyze the design. The study not only verified feasibility, but also resulted in a design of outstanding performance.

This was followed by a systematic exploration of system performance alternatives (which were based on component-level alternatives) to determine what combination of component performances is best to meet specifications yet minimize cost, weight, size and risk. The critical areas of brightness, resolution and color registration received special attention.

The optimized system configuration was then defined in detail electrically, optically, and from an equipment point of view. A detailed analysis of the performance characteristics was subsequently performed to verify compliance, to identify risk areas, and to point out areas of near-term-feasible performance growth.

The ultimate objective of arriving at a design which was easy to integrate into a full multiprojector system was considered in all phases of the study. Special attention was paid to ensuring that the resulting multiprojector system has the necessary attributes to attain high availability, i.e., high reliability, rapid fault isolation and repair, good accessibility and – most important – ease of system and projector alignment.

TABLE 2. STUDY OBJECTIVES AND APPROACH

Study Objective

- Develop conceptual design and detailed hardware/performance for high performance color television projector for CIG-driven, optically mosaicked simulators

Approach

• Requirements Analysis	• Understand, interpret and prioritize requirements
• Technology Survey	• Brief survey and analysis of current technology for candidates
• Component Investigations	• Broadbased investigation/development of all projector components (study and concurrent IR&D effort)
• Optical Subcontract	• Subcontract analysis of critical, complex component (two-phase design/optimization)
• System Trade-offs	• Quantitative analysis of critical areas; optimize for low risk/compliance
• Projector Definition	• Detailed conceptual design/definition of hardware and performance

3. REQUIREMENTS ANALYSIS AND TECHNOLOGY SURVEY LAID THE GROUNDWORK FOR PROJECTOR DESIGN

Two purely analytical tasks were undertaken as part of the study: a thorough analysis of the request for proposal (RFP) requirements, and a survey of applicable technology. The first effort began with a briefing by AFHRL on study objectives, system operational requirements, and the history and future plans for the wide angle FOV simulator visuals. This was followed by a visit to Williams AFB, Arizona with the HRL representative to observe the hardware and visual operation of the ASPT. Guidance was received from AFHRL in establishing priorities on the varied technical requirements. The information thus obtained was interpreted and expanded where needed to ensure that the requirements were well understood, as well as sufficiently comprehensive so that conceptual design of the projector could be initiated.

The second effort was a brief but comprehensive two-phase survey of the state of the potentially applicable display device art. At the outset, the field was quickly reviewed to verify that the proposed approach – liquid crystal light valve projector – was the best choice. The second phase had the same basic objective, but was conducted very late in the study to ensure timeliness of the survey conclusions. It was found in the second phase that General Electic (GE) had developed a 1000-line color light valve. This unit is the only available hardware that is within striking range of the required performance. Additive-color projection CRT techniques are low on light output, use very high voltages, and weigh too much. A liquid crystal light valve color projector can provide more resolution and twice the brightness of the 1000-line oil-film light valve system, with further improvements feasible. It remains, therefore, the clear technology choice for high resolution color optically mosaicked simulator visuals.

TABLE 3. HIGHLIGHTS OF REQUIREMENTS ANALYSIS AND SURVEY TASKS

Requirements Analysis

- Study/Observe ASPT System (Analyze Reports, Visit Williams AFB, Az)
- Determine Relative Importance of Requirements (Critical, Important, Desirable) with AFHRL Guidance
- Interpret Requirements – Document Results

Survey

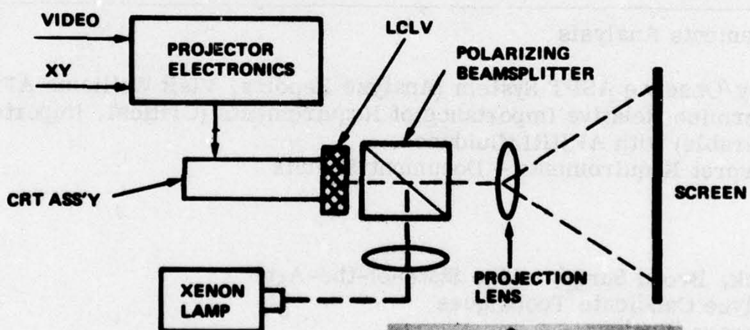
- Quick, Broad Survey of the State-of-the-Art
- Analyze Candidate Techniques
- Compare/Evaluate:
  - Additive Color CRT Projection
  - GE 1000-line color light valve
  - GE three projector 1000-line monochrome
- Concluded Liquid Crystal Light Valve Technology is Logical Choice

4. THE HDP-800 SINGLE-CHANNEL PROJECTOR PROVES PRACTICALITY OF LCLV CONCEPT

The selected LCLV approach has been shown to be a practical, attractive technique for generating a high quality projected image (see Figure 2 showing the HDP-800 projector built by Hughes in 1975 and now going into full production). The sensitive, high light-efficiency and high resolution liquid crystal light valve (LCLV) is the key to the features listed below. Driven by a high resolution, low power fiber optic CRT, the light valve produces a bi-refringent image in a thin liquid crystal layer which can be projected on a screen with the aid of polarized light, derived from an external light source and an efficient polarizing beam-splitter. The 10 kV CRT requires little power even at high deflection speeds, and forms, in direct contact with the LCLV, a small (14"), rugged, high-gain image generator unit.

Adaptation of this basic approach to an additive color system for optical mosaicking has many conceptual advantages. First, three image generators, sharing the same illumination system and projection optics, can provide full color capability with the aid of dichroics which split the white projection light into blue, green and red components. High resolution is obtained without much equipment complexity, with further growth is feasible. Because of the low light absorption of liquid crystals, high light levels – limited only by the light source – are attainable. The output is polarized, thereby doubling the effective efficiency of infinity optics used in simulators. The collinear, coplanar and collimated light beam makes distortion-free, high resolution optics achievable at low cost. Finally, low power, linear deflection amplifiers permit mixing of distortion or registration correction signals into the main deflection channel.

These features point to the LCLV technology as an excellent choice for implementing the RFP requirements. Proven performance of the HDP-800 is a solid foundation for the additive color configuration considered in this study.



- 800 LUMENS, 1000 LINES
- SINGLE CHANNEL COLOR
- SMALL SIZE (18" X 15" X 24")
- LOW WEIGHT (150 LB)
- RUGGED, RELIABLE

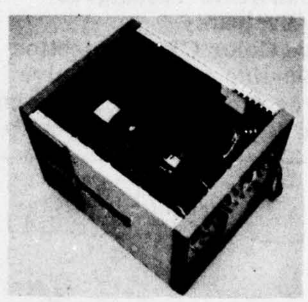


Figure 2. HDP-800 LCLV Projector

5. COMPONENT INVESTIGATIONS CONFIRMED THE FEASIBILITY OF THE LCLV APPROACH

A broad-based effort to explore and extend the performance of critical components of an additive color LCLV projector has resulted in significant progress in all areas. It is based on these investigations (some study funded, most of them funded by Hughes), that we can assert the feasibility of a color projector compliant with the requirements of the RFP.

Table 4 lists the basic components of the projector, together with their critical parameters and the progress made during the past year for each one. In some areas (lamp, prism, dichroics and projection optics) the performance required to support a compliant system was verified experimentally or by extensive analysis. For others (illumination optics, CRT), in-house breadboarding or component development has led to a thorough understanding of the techniques to achieve desired performance. These activities have shown that current performance can be extrapolated to the required levels with confidence.

While the liquid crystal light valve resolution, light efficiency, sensitivity and spectral response characteristics are more than adequate, and near-term compliance to contrast and uniformity can be predicted with confidence, the response time to accommodate the high-speed motion requirement is achievable with current technology only at the sacrifice of grey scale. This problem has been shown to be tractable; success depends on the level of R&D effort devoted to resolve it.

TABLE 4. ACCOMPLISHMENTS OF COMPONENT INVESTIGATIONS

Component	Critical Parameter	Status		
		Pre Study	Current	Predicted
Lamp*	Light Output	800 lumens	1600 lumens	X
Illumination*	Uniformity	±50%	±35%	±10%
Prism*	Stress Bi-refringence	Yes (Glass)	None (SiO_2)	X(1)
Dichroics	–	–	Feasible	X
LCLV*	Speed/Light Efficiency	See Text	60 ms/40%	30 ms/50%
CRT*	Resolution	2.0 mil	1.3 mils	1.1 mils
Optics	Feasible ?	Probably (?)	Verified	X
Curved Screen	Depolarization Ratio	No Data	Verified	X

* Conducted on IR&D funds (results reported in study)
X Current performance adequate
(1) Potential cost problem

6. KEY TRADE-OFFS ACHIEVED A BALANCE BETWEEN BRIGHTNESS, RESOLUTION AND FIDELITY REQUIREMENTS

The basic approach to implementing the required-performance projector is defined by the conclusions derived from system trade-offs in three critical areas: brightness (more correctly, light output), resolution and image fidelity (color registration, distortion, interwindow continuity).

Each of these parameters is affected by a number of the system components. To ensure a systematic approach toward optimizing the design, a comprehensive model was developed for each parameter (and other less critical parameters as well) and the range of available performances for each element in the model was defined based on component investigation results. Trade-off relationships defining total system performance as a function of the most critical, highest risk and greatest cost-impact elements were then developed. The results were plotted graphically whenever possible to gain a quantitative insight into critical interactions among these elements.

The selected combination of component performance was guided by the desire to "optimize" (within the constraint of meeting requirements) by equalizing risk across elements of each model. The resulting design – to the extent we succeeded in our optimization – is the most conservative design attainable, and does not depend on high-risk components to meet design requirements.

The hardware design approaches which have been selected as a result of these three system tradeoffs are presented in the "Recommended Approach" column of Table 5. The component improvements which will result in near- and long-term performance growth are presented in the right-hand column.

TABLE 5. RESULTS OF KEY TRADE-OFFS

	Recommended Approach	Growth
• Brightness	1.6 kW lamp	Eliminate relay
(250 lumens polarized light)	Relay optics to minimize risk	Increase LCLV η
	Based on measured LCLV η	2.5 kW lamp
	Broadband, 60 nm dichroics	
	High-η projection optics	
	Gain of 8 screen	
• Resolution	1.1 mil spot CRT	0.9 mil spot CRT
(30% MTF at 1000 TV lines)	Based on measured LCLV resolution	Improve LCLV resolution, sensitivity
• Image Fidelity	Initial mechanical alignment	Improve stability further
Color Registration (0.06%)	Analog correction circuits	Better fiber optics
Distortion (0.5%)	Digital correction memory map	
Interwindow Discontinuity	Stable (0.02%) deflection ckts	
	Reference slide in projector	

7. CONCLUSIONS AND RECOMMENDATIONS

The component investigations and the system trade-offs performed on this study conclusively established the technical feasibility of an additive-color liquid crystal light valve-based high resolution TV projector. Equally important, compliance with RFP requirements and "desirables" (high quality visual display, CIG compatibility, operation on motion platform, minimum weight, high availability) is achieved without compromising the long-term goal of developing a practical, reasonable cost, field-maintainable projector. None of the baseline components are excessively large, require excessive power, or are difficult to maintain; and the feasibility of integrating these components into a compact, lightweight and easily accessible/maintainable package has been verified.

A surprisingly high-availability multiprojector system is achievable by the baseline design. A system reliability of 1130 hours, means for system alignment without interaction between windows, and centralized minicomputer/disc hardware dedicated to supporting maintenance are the key concepts.

Since compliance is based on a conservative design approach, near-term performance growth in several areas critical to effective visual simulation can be implemented at minimal risk.

Based on the positive results of this study it is recommended that advanced development work should continue to reduce the few remaining areas of risk to demonstrable performance. Additionally, an effort to analyze growth areas in order to meet the needs of advanced simulator applications should be initiated.

TABLE 6. SUMMARY OF KEY CONCLUSIONS AND RECOMMENDATIONS

• RFP Compliant Projector is Technically Feasible/ Practical	• Excellent visual quality • Rugged and lightweight (280 lbs) • Maintainable and reliable (8000 hr MTBF) • Easily modified to implement multi-projector system
• Significant Near-Term Performance Growth is Achievable	• Increased resolution • Increased brightness • Reduced size/weight • Multitarget capability • Holographic pancake window compatibility
• Recommend Continuation of Advanced Development Effort	• Continue R&D to eliminate few areas of risk (CRT, relay, LCLV response, prism) • Verify interface with pancake window • Build feasibility model projector • Investigate multitarget capability

1. FUNCTIONAL DESIGN OF BASELINE PROJECTOR

A functional diagram of a full-color, 1000-line LCLV television projector is shown in Figure 3. Its operation is conceptually similar to that of the HDP-800 described earlier, with some of the following differences.

- **The white light-beam is split into three color beams (red, green and blue) using dichroics and trim filters.**
- **Each light beam is modulated independently with a 1000-line raster using three identical CRT/LCLV image generators.**
- **Analog (orthogonality, gamma correction) and digital (correction memory) circuitry is added to permit accurate aligning of the three deflection and video channels; and gain/offset-stable circuits are incorporated to maintain color registration of the projected image once aligned.**
- **Lamp power is increased to 1,600W to compensate for losses in the dichroics and in the optical system.**
- **Projection optics are redesigned to accommodate the 24"-radius curved screen and the optical mapping characteristics required, and to compensate for the long back focal length needed for the dichroic assembly.**
- **A hemispherical, high-gain, nondepolarizing screen is provided.**

The projector also incorporates digital test pattern generation and storage to facilitate system alignment and troubleshooting. Organization of the electronics assumes that the projector is operating as part of a full-cockpit multiprojector simulator; a central minicomputer/disc facility (not shown) is therefore provided to store and recall test patterns, to aid with setting up the correction memory of all image generation channels (3 x number of projectors), and to assist with other maintenance functions.

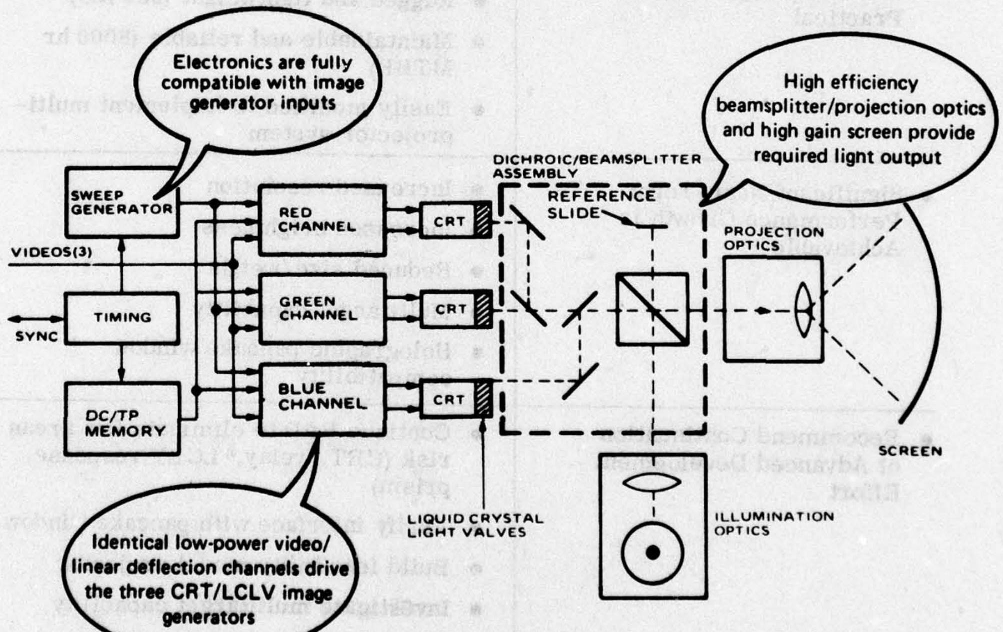


Figure 3. Functional Diagram of Full Color LCLV Television Projector

2. PHYSICAL CONFIGURATION OF BASELINE SYSTEM

Figure 4 shows a top (rear) layout of the recommended projector. The basic structure is a three-inch-thick honeycomb/aluminum plate sandwich which serves as a rigid, optically flat foundation for coplanar mounting of all optical components. Coplanarity minimizes sources of distortion error and simplifies alignment. The lamp, the dichroic assembly, and the projection relay optics are prealigned optical assemblies which fasten directly onto the plate.

The baseline illumination optics conservatively incorporate a long relay system which occupies a sizable area on the plate. Expected development of a proper focal length reflector for the xenon lamp will eliminate the need for the relay, and both increase light output and reduce projector size/weight.

All platform electronics – consisting of channel deflection/video/CRT circuits in a 22-card cardbox, deflection amplifiers, and high voltage and deflection amplifier power supplies – are mounted underneath the plate. Regulated power is supplied to all projectors from a centralized, redundant power supply rack.

A full cockpit multiprojector system (shown in Figure 5) is implemented by rigidly mounting the projectors with lightweight support struts attached between the optical plate and the dodecahedron frame which surrounds the cockpit and mounts the pancake windows. The projectors are mounted perpendicular to a pentagonal side for alignment with the pancake windows, and can be oriented in either of two directions to simplify access. The screen is mounted directly to a plate which is attached to the dodecahedron frame, independent of the projector.

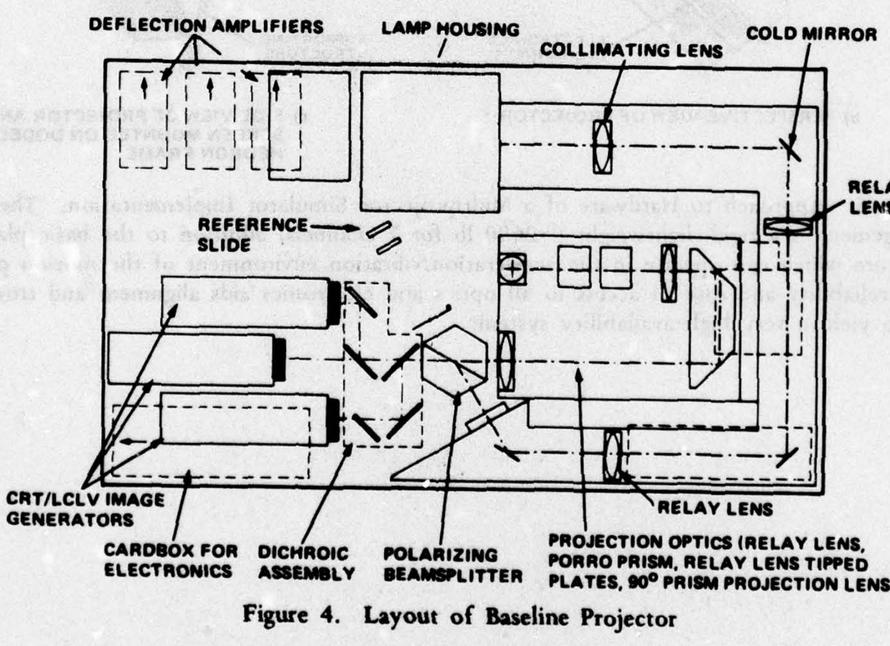


Figure 4. Layout of Baseline Projector

2. PHYSICAL CONFIGURATION OF BASELINE SYSTEM (Continued)

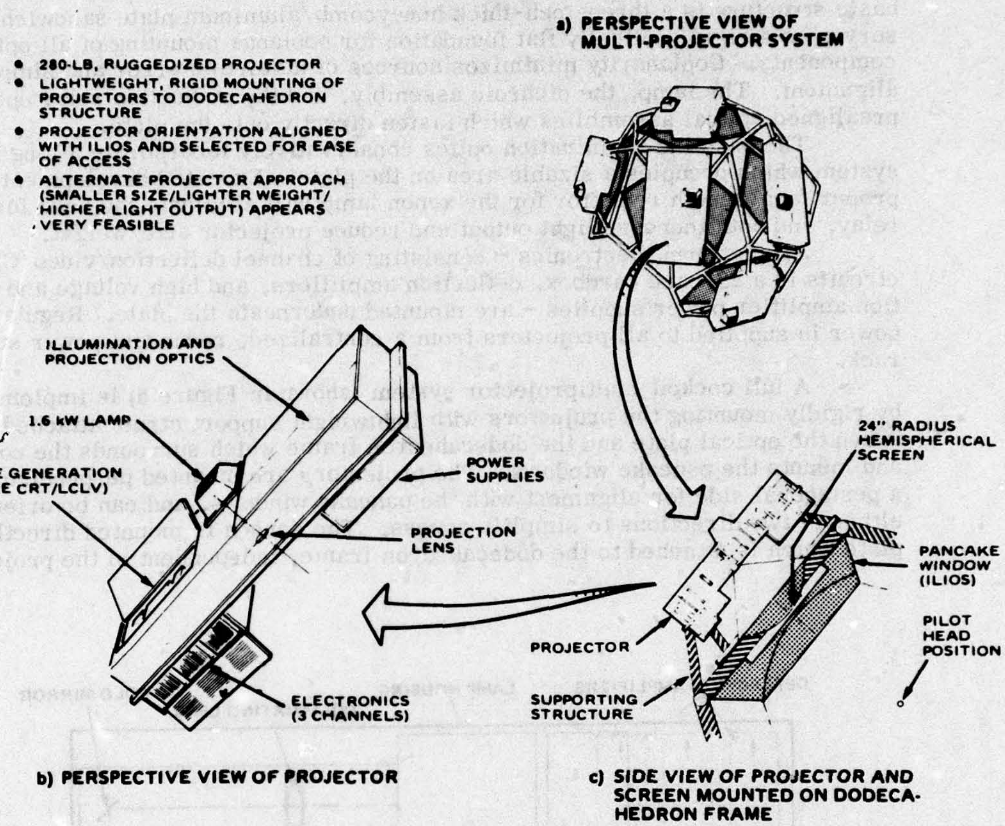


Figure 5. Approach to Hardware of a Multiprojector Simulator Implementation. The resulting arrangement is a rigid, lightweight (~2600 lb for 7 channels) addition to the basic platform structure which can operate in the acceleration/vibration environment of the motion platform. High reliability and ease of access to all optics and electronics aids alignment and troubleshooting to yield a very high availability system.

3. BASELINE SYSTEM FEATURES

The high visual quality, system flexibility, and attractive hardware characteristics of the basic projector translate directly into a high-availability, multiprojector, full-cockpit simulator visual system capable of providing the pilot with a realistic CIG simulation of the real world.

The projector features near-compliant performance in the visual area, and provides visual quality which far exceeds that available from other state-of-the-art techniques. Modulation transfer function (MTF) of the projected image is 30% at 1000 lines (which is equivalent to 1500 TV lines limiting). Brightness of the baseline system is 250 fL polarized, yielding an effective brightness of 500 fL through the pancake window. Brightness uniformity, and contrast although falling slightly short of RFP requirements will not introduce noticeable degradation to image quality. Color range and purity will be as required, with color misregistration held to one-half line width, worst case. Response time required to support high speed motion will be met with an improved LCLV. Significant growth capability is feasible in resolution and in brightness with additional development effort. The projector readily interfaces with the specified CIG. The hardware is lightweight (280 pounds baseline, 240 pounds alternate), ruggedized to take motion platform vibration and acceleration, and has high reliability. The projector is designed to facilitate accurate mosaicking with adjacent projectors in a full-cockpit arrangement. Brightness variation and inter-window discontinuities are held low by good distortion control and by a systematic alignment procedure featuring reference slides, digital correction memories, and test patterns. These features, coupled with basic high projector reliability and redundant central power supplies yields a multiprojector system with not only high mission-critical reliability (1130 hours for 7 channels) but ease of alignment/troubleshooting as well.

TABLE 7. SUMMARY OF BASELINE SYSTEM FEATURES

BASIC PROJECTOR FEATURES	MULTIPROJECTOR SYSTEM FEATURES
High Visual Quality • High Brightness (with Growth) • 30% MTF at 1000 TV Lines • Full Color • Response Time Nearly Adequate	**Accurate Mosaicking** • Brightness Variation < ±17.7% (rms) • Interwindow Discontinuity 1%
Interface Flexibility • Linear Deflection • Correction Memory for Distortion	**High Availability** • Mission-Critical MTBF of 1130 Hours • Many Maintainability Features • Central Minicomputer and Dual Discs for Test Patterns, Diagnostics, Computer Aided Alignment • Reference Slide for System Alignment on a Projector-by-Projector Basis
Hardware Characteristics • Weighs 280 pounds (240 pounds Alternate) • Ruggedized to Take Shock • 8000 Hour MTBF • All Components Easily Accessed	**Compatibility with Motion** • Rigid Mounting of Projectors to Dedecahedron Structure • Total Weight on Platform is Approximately 2600 pounds for 7-channel visual system

PRECEDING PAGE BLANK - NOT FILMED

SECTION 2
REQUIREMENTS ANALYSIS

1. SUMMARY OF KEY TECHNICAL REQUIREMENTS

Prioritizing, interpreting and expanding on the requirements was the first task in the study. The results of that task are summarized here.

This section outlines the technical requirements for the high resolution, high brightness color TV projector defined in the study. The projector is intended to operate as a direct replacement for any one of the CRTs in the ASPT; further, it must be capable of generating a wide field-of-view by being mosaicked together in the dodecahedron configuration developed for ASPT. In general, the RFP for the study clearly delineates the overall requirements. However, in some areas additional clarification is required; in others, the pecularities of the liquid crystal projector create the need to refine the requirements further. This was the objective of the first study task.

A summary of the technical requirements is given in Table 8. The requirements are classified as being "critical", "important", and "non-critical", in order of relative importance. This ordering was done to permit meaningful trade-offs to be made among performance parameters. "Critical" requirements are those which must be met or else the realism of the wide-field-of-view display seen by the pilot in the final (dodecahedron) configuration is seriously degraded. RFP requirements represent the minimum acceptable performance. "Important" requirements are those for which the RFP specifications should be met if possible and where cost-effective even if some of the "non-critical" requirements are compromised in the process. The "non-critical" requirements are those most readily traded off for the sake of meeting performance for "critical" or "important" parameters, or for the sake of lowering cost and improving reliability.

"Desired" performance is listed for all requirements for which performance exceeding that specified in the RFP materially improves overall system effectiveness. Estimated values for desired performance are tabulated in the right-hand column.

TABLE 8. TABULATION AND CLASSIFICATION OF TECHNICAL REQUIREMENTS FOR THE COLOR PROJECTOR

Parameter	Criticality(1)	RFP Requirement	Desired*
Image Requirements			
Brightness	I		
Unpolarized,		480 fL	1000 fL
Polarized		240 fL	500 fL
Brightness Variation			
Across Screen	NC	25%	–
Edge-to-Edge	C	12%	–
With Head Motion	NC	not specified	50%
Contrast Ratio	I	25:1	25:1
Resolution			
Horizontal Center	C	30% @ 1000 TV lines	(2)
Horizontal Edge	C	35% @ 750	(2)
Geometric Distortion			
Edge	C	1.0%	0.5%
Center	I	1.0%	0.5%
Interwindow Discontinuity	I	not specified	1.0%
Color			
Range	NC	P22	–
Spatial Uniformity	I	not visible	–
Constancy	I	not visible	–
Registration	I	not specified	0.06%
Persistence	I	no color shift	–
		no smearing	–
		single frame writeup	–
Electrical Requirements			
Video	C	see Topic 2-3	–
Stability	C	0.5%	0.2%
Alignment	C	see Topic 2-3	–
Video Bandwidth	C	20 MHz ±1 dB	30 MHz @ 3 dB
Risetime	C	25 ns	15 ns
Interface	C	see Topic 2-3	–
Optical Requirements			
Mapping	C	see Topic 2-3	–
Display Configuration			
Pentagonal	C	89^o pentagon	–
Rectangular (1:1 or 4:3)	NC	half angle of 45^o	–
Flat Screen (1:1 or 4:3)	NC	$60^o \times 60^o$, $60^o \times 80^o$	–
Mechanical/Environmental			
Motion			
Orientation	C	any angle	–
Acceleration	C	see Topic 2-4	any motion platform
Weight	I	minimize platform weight	–
Temperature	I	60-85^{o}F	–
Humidity	I	10-60%	–

(1)C = Critical, I = Important, NC = Non-critical
(2)As high as possible
*"–" means "same as RFP requirement"

2. CLARIFICATION OF IMAGE REQUIREMENTS

Critical image requirements include minimum brightness variation across adjacent screen edges, resolution across the screen and minimum geometrical distortion at the screen edge.

Brightness – This is an important requirement. While a lower brightness level might be acceptable it is clearly undesirable. The RFP requirement of 480 fL assumes unpolarized light emanating from the spherical surface. If light is polarized and the direction of polarization lines up with the polarization axis of the pancake window, the brightness requirement is halved (240 fL). To use this lower value, means of lining up the polarization of the projector output with the axis of the first polarizer in the pancake window must be provided. Note that the polarization axis of the pancake window is always perpendicular to one side of the pentagon which defines the circumference of the window.

Brightness Variation Across Screen – This is a non-critical requirement. Although good uniformity is desirable to avoid further degradation in brightness, uniformity (over and above the degradation introduced by transmission non-uniformities in the pancake window), it is felt that a brightness variation (Bmax-Bmin/Bmax) of as much as 50% (or ±25%) would yield a very acceptable display. However, variation in brightness must be gradual, and sharp gradients must be avoided.

Brightness Variation Across Edges – This has been identified as a critical requirement, with less than 12% variation across two screen edges. It is proposed to treat this as an "important" requirement, and raise the acceptable brightness variation to 30% (while keeping 12% as the goal) for the following reasons:

- Pancake window transmission can vary as much as ±20% around the periphery.
- Dark metal strip defining outline of each facet minimizes sensitivity of the pilot to changes in brightness.
- Since brightness variation around the periphery can be caused by lens light falloff, and non-uniformity in screen gain, in the light valve and in illumination, achieving a 12% tolerance will be extremely difficult.

Given the variation due to the pancake window (40%), the % increase in brightness variation across the edge due to relaxing the tolerance on the projector from 12% to 30% is only

$$\frac{(40 + 30) - (40 + 12)}{(40 + 12)} = 34.6\%$$

and appears to be a cost-effective compromise.

Brightness Variation as a Function of Pilot Head Motion – The CRT used in the monochrome system is a Lambertian source of radiated light; i.e., the apparent brightness of a displayed object is invariant with the angle from which it is viewed. In a system in which a screen with directional properties is used, the variation in brightness as a function of pilot head motion must be specified. This falloff will manifest itself as a decrease in image brightness for every point on the display for which the "viewing-line-of-sight" is not radial. The effect of this varies as a function of pilot head motion direction. When the head moves forward, the brightness in the center of the display will remain constant, but there will be a gradual falloff around the periphery. When the head moves perpendicular to the forward direction (i.e., it moves to the side), there will be a (nearly) uniform decrease in brightness of the whole display.

Since the falloff is gradual, a brightness variation of 2:1 in average brightness(1) over the viewed display as the pilot's head moves within a 6" radius sphere is not expected to be objectionable, and will be established as a design goal. A variation of 1.5:1 is established as a desirable goal. Furthermore, the percentage differential brightness(2) should be held below 50%.

Contrast Ratio – Contrast ratio is defined as CR = Bmax/Bmin and is considered an "important" parameter. Since in a full-color system, color (as opposed to shades of gray) will be the primary cue for differentiating and recognizing objects in the visual field, high contrast – with the implication of a large number of shades of gray – would appear to be much less critical than for the monochrome system. A contrast ratio of as low as 15:1 might be acceptable.

Resolution – Resolution is a critical requirement since it has direct bearing on image information content. Resolution must be measured at the screen to account for resolution losses in the video chain: CRT, light valve, projection lens and screen. Resolution is best specified in terms of a square wave MTF response(3) at the maximum rate at which the system can be modulated. For horizontal resolution, the maximum modulation rate is represented by on-off modulation of successive elements, equivalent to 500 cycles, or 1000 TV lines. Both center and edge response should be specified at this value. The required square wave MTF response at the center is 30%, and at the edge is 15%. The latter figure is equivalent to a 35% response at 750 TV lines, the resolution specified in the RFP. Equivalency is based on the assumption that the shape of the MTF curve is Gaussian; this assumption appears to be reasonable.

Geometric Distortion – A critical requirement. Deviation from the ideally mapped position must be held below 1% of screen height to minimize mismatch across adacent edges; lower distortion (e.g., 0.5%) is desirable. While edge matching is the critical consideration here, *distortion within the display should still be* below 1%.

Color Range – A non-critical requirement. Range of colors should match those obtainable with P22 phosphor; this will ensure that an acceptable range of colors will be available on the one hand, and that the system will be compatible with National Television Standards Committee (NTSC) color standards on the other.

Color Spatial Uniformity – An important parameter. Variation in color as a function of spatial position should not be discernible to the pilot.

Color Constancy – This is an important parameter. Color changes as a function of brightness should be minimized so as to be indiscernable.

Persistence – This is an important requirement. High speed motion of the visual scene must be presented to the pilot without any appearance of "smearing" in the display. It is estimated that this implies a decay of the displayed image to 10% of its original brightness in one frame time (33 ms) assuming that image decay is exponential. The capability to present a high speed motion visual scene also implies single-frame writeup of the image to ensure brightness consistency with image motion.

Color Registration – This is an important requirement. Poor registration will cause *color-fringing. Misregistration* between any two color channels must be less than one line width, 0.1% over the full screen, and should be held to less than 0.06% as a design goal.

---

(1) Average of brightness seen by the two eyes $B_A = (B_{RE} + B_{LE})/2$
(2) Differential brightness is defined as $B_D = |B_{RE} - B_{LE}|/B_A$
(3) MTF Response is defined as *MTF = (Bmax - Bmin)/(Bmax + Bmin)*

3. CLARIFICATION OF ELECTRICAL AND OPTICAL REQUIREMENTS

Electrical requirements affecting computer image generation (CIG) compatibility, image drift, image alignment, and image resolution are all critical. The mapping correction of the optical system is also considered critical.

ELECTRICAL REQUIREMENTS

Video Input – This is a critical requirement to ensure compatibility with the ASPT CIG. The videos for each channel must be non-composite, and be in accordance with Electronic Industries Association (EIA) Standard R343 (except that Section 2.5 of this standard does not apply, and the words "television camera" shall be replaced with "CIG"). Video input cables must be terminated in 75Ω.

The video signal will have the following characteristics:

- 1023 scan lines/frame, 985 active lines
- 30 frames per second, 2:1 interlace (60 fields/sec)
- Horizontal resolution elements: 1000
- Raster aspect ratio: 1:1.

Stability – This is a critical requirement. Image drift must be less than ±0.5% around nominal position. Note that in order to meet color registration requirements (see above) image drift should be considerably better than ±0.5%, unless drift is common-mode drift.

Alignment – Incorporation of the capability required to align the polarization axis of the projector to any of the seven windows in the cockpit, and to align the projected image with respect to the neighboring windows to minimize edge discontinuities, is a critical requirement.

To provide for alignment of the projected image with the neighboring windows, means of rotating the raster to align it with any edge of the pentagon must be provided. This should be implemented by a combination of gross mechanical adjustments and a fine electrical adjustments. To ensure high light transmission to the pilot, means of mounting the projector such that its axis of polarization is aligned with that of the pancake window must be provided as discussed above. The range which the positioning rotational and gain adjustments should cover are estimated to be as follows:

Gross rotational	±180°	mechanical
Fine rotational	±5°	electrical and mechanical*
Vertical position	±10%	electrical and mechanical
Horizontal position	±5%	electrical and mechanical
Size	±5%	electrical and mechanical

Video Bandwidth – This is a critical requirement in that it affects resolution. Minimum requirements are as specified in the RFP: 20 MHz ± 1 dB with pulse response fall time of less than 25 ns with less than 10% overshoot. It is likely that to meet the horizontal resolution requirement it will be necessary to decrease rise time to 15 ns.

Interface – This is a critical requirement. The projector must be capable of interfacing with the ASPT type CIG image generator. The generator has an element rate of 40 MHz, and provides the following signals in addition to three videos.

Element rate clock pulse	40 MHz
Horizontal blanking	7 μs
Vertical blanking	619 μs

Amplitude of these signals will be standard transistor-transistor logic (TTL) levels (+3V minimum).

*Mechanical adjustment only occurs during initial alignment.

OPTICAL REQUIREMENTS

Mapping Correction – This is a critical requirement. The display system must convert the display video which is derived in the CIG from a computational display plane into an image that is viewed by the pilot in spherical coordinates. The display shall provide the following transformation between object distance from the display center on the computational display plane (y) (i.e. the video image generated by the CIG) to the image chordal height (referenced to the display axis) on the spherically curved screen (Y)

$$Y = k_1 \sin (\tan^{-1} \frac{y}{k_2})$$

where k_1 is the radius of the screen, and k_2 is the effective back focal length.

Display Configurations – Three display configurations must be considered.

a) Spherical screen, pentagonal optics. A 1:1 raster is generated by the CIG; however, the pilot will only be able to see a pentagon inscribed in this raster. The bottom raster line is one of the pentagon edges. The vertices of the projected pentagon lie on a chordal plane generated by a cone concentric with the hemispheric screen, and having a half angle of approximately 45^o.

b) Spherical screen, rectangular optics. A rectangular (1:1 or 4:3) raster displayed on the image generator is fully displayed on the screen. The vertices of the projected rectangle lie on a chordal plane generated by a cone concentric with the hemispheric screen, and having a half-angle of approximately 45^o degrees.

c) Flat screen, rectangular optics. The full CIG-generated raster (which is either 1:1 ($60^o \times 60^o$) or 3:4 ($50^o \times 69^o$) is displayed on a flat screen. Maximum projection half-angle (to the vertices of the projected rectangle) must be equal to 45^o.

4. CLARIFICATION OF EQUIPMENT-RELATED REQUIREMENTS

The color television projector hardware characteristics are based on the following basic requirements: 1) operation in a fixed site having air-conditioning; 2) capable of being mounted on an ASPT-type dodecahedron mosaic frame structure; 3) the ability to withstand the shock, vibration, and linear/angular velocities and acceleration of an ASPT-type motion platform; and 4) provide good accessibility to all projectors in the final system. Furthermore, it is desirable to minimize both weight and angular momentum around the platform axes.

Operating Environment – Operation in a fixed air-conditioned building implies operating and non-operating temperature between 60 and 85°F, and humidity range of 10% to 60%.

Mounting to Motion Platform – The projector (and supporting structure) must be mounted to the dodecahedron frame which surrounds the cockpit, and which supports the pancake windows. Projectors must be capable of being mounted at any attitude, and will undergo a rotation of +38 to -20°; the projector shall be fully operational under these conditions.

Each projector must be mounted to align the axis of polarization of the projector with that of the pancake window. In the pancake windows observed at Williams AFB this axis was always perpendicular to one side of the pentagonal frame. Means of fine-tuning alignment of the two axes of polarization must be provided.

Motion Platform Operation – As specified in the RFP, the basic requirement states that the unit shall be capable of operation on an ASPT-type motion platform. The table below shows measured motion platform accelerations.

Roll – ±8 Radians/Sec^2
Pitch – +10.1, - 9.1 Radians/Sec^2
Yaw – ±16 Radians/Sec^2
Longitudinal – +1.05 g's, -1.35 g's
Lateral – ±1 g
Vertical – +4.3 g's, -3.1 g's

The linear acceleration is derived from the angular figures and estimated distance of platform-mounted projector from the center of platform rotation. Based on these numbers, it is estimated that the projector must be capable of withstanding a linear acceleration of 5 g's.

Accessibility – It is expected that all maintenance actions will be performed with the projector mounted. Hence components/subassemblies requiring monitoring during maintenance actions, or removal in case of replacement shall be mounted to permit easy access. Since the exact means of gaining access to the projectors is indeterminate – ladders, catwalks, hoists are possibilities – this requirement is general in nature.

Weight/Configuration – This is a critical requirement. Weight on platform (projector plus cables) must be kept below that of the currently installed CRT, electronics, and cables (~500 lbs.); furthermore, it should be minimized.

SECTION 3
TECHNOLOGY SURVEY

1. SURVEY OF APPLICABLE TECHNOLOGIES

Consideration of the RFP requirements of color, high brightness and high resolution rapidly narrows the choice of technologies to a few plausible candidates. Comparing candidate systems in each plausible technology to the design requirements clearly shows that the liquid crystal light valve technology is the best possible choice.

A brief survey of the state of the color television projection art revealed early that the LCLV projector represents by far the best choice for meeting the design requirements. Consequently, the bulk of the study effort was devoted to optimizing this approach. Before the study was completed the field again was surveyed to uncover any techniques/hardware which may have emerged during the past nine months which, although not capable of meeting the design requirements in their current state, are capable of being improved to meet these requirements.

The survey was divided into two phases with most of the emphasis on the latter phase. In the first phase, all large screen projection techniques were evaluated superficially with regard to feasibility of compliance, availability and risk. The second phase examined in greater depth candidate techniques, extrapolated their current performance within practical limits toward the design requirements, assessed potential problem areas, and considered technology risk areas.

A great variety of techniques for projecting TV images have been devised during the past few years. The most important of these may be classified into one of three categories: CRT projection systems, light valves, and light beam scanning systems.

<u>CRT Projection Systems</u> – Cathode ray tube (CRT) projection systems use a CRT designed for high light output (high beam current, high screen voltage), and project the phosphor image on the screen with the aid of a reflective or refractive lens. The basic challenge is getting high brightness on the screen. Recent developments include CRTs with sapphire faceplates (to conduct the heat away) capable of generating up to 30,000 footlamberts (fL) at high resolution and brightness levels, and high efficiency (f/0.55 to f/0.8) reflective and refractive optics. Several CRT projection systems generate a high quality image, and were considered in some detail.

<u>Light Valve</u> – A light valve approach to generating a projected image is conceptually attractive because it is inherently capable of more light. Light output is limited only by the external light source (which can be made very bright), and the ability of the light valve device to take the heat absorbed from the illuminating light beam. Good summaries of various light valve techniques may be found in the literature* and therefore no attempt will be made to describe them. Their applicability to the ASPT requirements is assessed as follows:

- Oil Film Light Valves. Two types exist: transmissive, and reflective. The former are potentially applicable and were evaluated in detail. The latter although capable of very high light output (7000 lumens) are complicated, large, expensive monochrome devices which cannot withstand the motion platform environment; furthermore, three projectors are required to generate a color picture. These factors eliminate them from further consideration.

---

*H. Hendrickson and J.D. Stafford, "Television Projectors," Proceedings of the SPIE simulator Conference, 1975.

- Deformographic Light Valve. This concept has not successfully solved the problem of writing at television rates, nor does it have the required light output. Cost and nonavailability are other reasons for judging the technique unacceptable.
- Titus Tube. This is a solid state color light valve which has good potential for commercial color television, although it is still in the R&D stage. Since the resolution required by ASPT is three to four times greater than that of commercial TV, great improvements in resolution are necessary before this could be considered a viable technique for simulation.
- Liquid Crystal Light Valve (LCLV). This device is a good candidate, and is evaluated below.

Other light valves are either low performance or not yet practical (usually both) and need not be considered.

Light Beam Scanners – The light beam pointing approach scans a focused light beam to paint a raster, and modulates the beam with video to generate an image. Using a laser (or three lasers) as a light source, the technique is potentially capable of high resolution and high brightness, and can be projected on curved surfaces with minimal defocusing. Recently, electronic scanners have been built and high bandwidth modulators are practical. The major (and decisive) shortcoming is the poor efficiency of both the lasers and the deflectors/modulators. A recently built system is reported to require 75 kW power to generate 300 lumens of useful light – an overall efficiency of only 5/75000 = 0.0006 percent. Clearly, further improvements are in order before laser displays can be considered practical for this application.

Analysis of Candidate Systems – Based on the above, only the LCLV, the transmissive light valve and projection CRTs appear to be reasonable candidates. During the study, different configurations using transmissive light valve and CRT projectors were examined and evaluated. Where possible published information on projector performance was used in the evaluation. Where such data was not available (e.g., additive color wide-field-of-view projection on a curved 24" radius screen with either monochrome light valves or CRTs) performance was estimated. The results of the evaluation are summarized in Table 9. Based on its ability to provide both the required light output and resolution and its potentially excellent reliability/maintainability characteristics and hardware features, the LCLV projector emerges as the clear technology choice.

Additional information on the survey and comparison of candidate projector types is provided in the AFHRL-TR-77-33 (II) (limited distribution) addendum.

TABLE 9. SUMMARY EVALUATION OF PRIME CANDIDATES

Requirement	Candidate		
	Transmissive Light Valve	CRT* Projection	Liquid Crystal* Light Valve
Light Output	XX	XX	–
Resolution	XX	–	–
Weight/Size	–	XX	–
Reliability/Maintainability	X	X	–

X – shortcoming XX – major shortcoming *Additive color

Preceding Page BLANK - NOT FILMED

SECTION 4
COMPONENT INVESTIGATIONS

1. SUMMARY OF COMPONENT INVESTIGATIONS

Overall system performance is clearly dependent on the performance of individual components. Components unique to the RFP requirements (lens, dichroics, deflection, screen) were investigated on study funds to establish the range of feasible and cost-effective performance, while other system components were being studied concurrently under Hughes internal R&D funding.

Initial analysis of system performance indicated that to meet design requirements necessitated improvement of virtually all components in both the optical and electrical system of the HDP-800 single-channel projector. This projector was the hardware base on which the feasibility of an ASPT-compatible color projector was originally established. A Hughes' on-going internally funded R&D (IR&D) program investigated all of the components except those unique to the study baseline system (e.g., projection optics, the dichroics, deflection system and the curved screen). These latter components were investigated with study funds. To avoid compromise of proprietary information, the studies conducted with IR&D funds will be described only to the extent necessary to support study recommendations.

A list of component investigations with summary conclusions of the data gathered and the measurements taken for each is presented in Table 10. Subsequent topics will describe (with the exception of the MacNeille prism discussed here) in more detail the approach taken in each area, current status of component development and future development plans/recommendations. The most critical component investigation (the projection lens) was handled as a design study subcontract to Kollmorgen Corporation. The results of each phase of their two-phase study are summarized in Topics 4-8 through 4-11.

The polarizing (MacNeille) prism is an important element in the system. Its characteristics affect contrast, light output, spectral bandwidth and (if improperly designed) brightness uniformity. When the HDP-800 was first built, a high-lead glass prism was employed. Experience with operating the system pointed to the need for a prism made of low-stress bi-refringent material to avoid depolarization of the projected light when thermal stresses develop as a result of high incident light levels. A sample prism built with fused silica demonstrated that this material eliminates the depolarization problem. The angle between the incident light and the polarizing surface in a fused silica prism is 58^{o} (instead of 45^{o} for glass), causing a rearrangement of the optical path used in the HDP-800. One potential problem is the cost of a prism of the size required to accommodate the long-throw, wide f/8 light beam.

In general, the feasibility and availability of all the components necessary to meet the design requirements and implement the recommended projector (see Section 6) have been verified either experimentally or by analysis. Further work is required on the CRT, the LCLV, and the projection screen. Continued R&D work in the first two areas is expected to yield desired performance, while the projection screen is considered both a low cost and low risk item.

TABLE 10. SUMMARY OF COMPONENT INVESTIGATIONS

Component	Investigation Summary
Cathode Ray Tube (CRT)*	• Had high resolution CRTs (1.1 and 1.5 mils) developed • Ran tests on focus coil aberrations • Initiated program for further resolution improvements
Deflection System	• Analyzed requirements • Developed correction memory technique for good color registration • Developed concepts for gain/offset stabilization
Prism (see text)*	• Developed high contrast fused silica prism
Illumination Optics*	• Tested candidate light sources; measured aperture distribution • Implemented and tested illumination system • Considered impact of improved optics (elliptical reflector) on illumination optics
Liquid Crystal Light Valve*	• Constructed TV cells of good quality • Conducted resolution, efficiency, time response, sensitivity and contrast tests on these cells
Dichroics	• Let study subcontract to analyze efficiency and spectral shift in dichroics • Conducted narrowband (30 nm) visual evaluation using off-the-shelf filters • Developed computer program to perform color analysis* • Analyzed cells with program
Projection Optics	• Let two-phase study to Kollmorgen • Phase I: selected lens type • Phase II: Conducted performance tradeoffs; optimized, defined and priced the selected lens
Screen	• Surveyed vendors field, and obtained samples • Tested samples for gain and depolarization ratio

*Conducted under IR&D funding.

Preceding Page Blank - NOT FILMED

2. CATHODE RAY TUBE (CRT) INVESTIGATIONS

Based on an extensive investigation of both in-house and vendor built and tested/measured CRTs, the feasibility of obtaining a CRT with the requisite spot size to meet system resolution needs can be predicted with confidence.

Early in the study preliminary requirements were established for the CRT, based on an estimate of the resolution realizable in the other projector components and the sensitivity of the liquid crystal light valve. The key requirement was established to be a center spot size of 0.0013 inch (or 1.3 mils) at a brightness of 200 footlamberts (fL) at a writing rate of 64,000 inches/second. Subsequently, system tradeoff studies based on measured LCLV performance and the results of the projection lens design study indicated that a spot size of 0.9 or 1.1 mils was required to meet system resolution requirements with the "standard" and "high quality" projection lens designs, respectively.

The CRT investigation proceeded in parallel utilizing both internal IR&D program development activities to improve resolution of the small (1.0 inch) neck CRT used in the HDP-800 projector as well as investigating and obtaining several types of sample tubes from CRT manufacturers. Testing and assessment of performance was accomplished.

It is concluded that while further CRT development work is required, obtaining either a 0.9 or 1.1 mil spot size at 200 fL represents a minimal technical risk.

In parallel with the CRT investigations, the high numerical aperture fiber optic plates used both for the CRT faceplate and the LCLV substrate were also investigated. Suitable sources for the multi-multifiber bundle type plates were found. Several faceplates were evaluated and characterized with respect to the image distortion they introduced. While gross (low spatial frequency) distortions can be compensated for by the digital correction memory, localized image distortion (e.g., shear) may not be compensatable. It is expected that high quality, high coherence fiber optic plates will be required for both the CRT and the LCLV.

Additional information on CRT investigations is provided in the AFHRL-TR-77-33 (II) (limited distribution) addendum.

3. RESULTS OF DEFLECTION SYSTEM INVESTIGATIONS

An analysis of three different CRT deflection systems indicates that a separate, chopper stabilized, low power (200 W) deflection amplifier pair for each channel yields the lowest risk approach.

The color registration requirements (0.06 percent) clearly point to the need for a drift-free (0.02 percent), high gain stability (0.01 percent) deflection system in each channel to maintain color registration (for detailed analysis, see Topic 5-6). Since the deflection system must be linear to allow insertion of correction voltages, the simultaneous implementation of high power operation and extremely high stability is a technical challenge. It was decided to utilize feedback on a maximum deflection signal to maintain gain stability to 0.01 percent. This is a less critical problem than that of offset drift. A tradeoff study was therefore conducted among three approaches considered candidates to meeting the offset drift requirement of 0.02 percent. The results of the study are summarized below.

Series-Driven Yokes - In this configuration a single amplifier drives the three yokes in series (part A of Figure 6). A single, common, sense resistor (Rs) is used, which eliminates differential drift between channels due to change in the value of Rs as a function of temperature or age. It is necessary to trim the yokes to ensure application of correct voltage across each one, and to compensate for differences in yoke sensitivities.

The major disadvantages of this approach are as follows. 1) The series combination of three 50 μh yokes requires a slew voltage of 218 V, which complicates the design of the amplifier. (High bandwidth, high voltage output-stage transistors tend to be costly and unreliable.) 2) Two convergence amplifiers/yokes must be added to each channel to insert the distortion compensating correction signals.

Parallel Driven Yokes – In the parallel driven yoke configuration (part B of the figure), the deflection amplifier for the three channels supplies a slew voltage of 56 volts. (This voltage is more reasonable than that required for series driven yokes.) The series resistor, in conjunction with the convergence amplifier, controls the balance of the X and Y deflection for each channel, which eliminates the need for three convergence yokes. Although the advantage of minimizing differential drift between channels is lost in this configuration, a flyback or equivalent switching technique can be used to generate sweeps, which simplifies the high voltage circuit.

This deflection method has two major disadvantages: 1) The use of separate sense resistors provides a differential drift factor between channels, which is not experienced in the series method (although three identical channels should minimize the differential error to a usable level.) 2) The convergence amplifiers require differential input with excellent common-mode rejection because the output forms the reference for the yoke sense resistor. The output error generated by the sense resistor and convergence amplifier must be less than 0.02 percent to limit the channel-to-channel misregistration to one-half line width.

Separate Deflection Amplifiers – To eliminate both the convergence amplifiers and the convergence yokes, the deflection yokes can each be driven and corrected separately (part C of the figure). This method of deflection generation has attributes of both the series and parallel methods inasmuch as the yokes are driven separately but from the same sweep generator. The high-current, flyback sweep generation technique is replaced by a low voltage, low power sweep generator, but the slew voltage required is still high (56 volts). The separate amplifier method has essentially similar disadvantages to the parallel method without the flyback system. However, analysis indicates that chopper stabilization of each amplifier will reduce offset drift to 0.02 percent or less.

Conclusion - An evaluation of the data in Table 11 shows the series approach to be a high risk option, which makes it the least attractive and eliminates it from consideration. Although the parallel method is lower in cost and uses less power than the separate deflection method, it presents a higher technical risk with the high current usage in the flyback circuitry. The separate deflection method using an existing circuit which is chopper stabilized to eliminate drift represents the least technical risk, and has the highest reliability. Although it consumes more power than the first two techniques, and uses more expensive amplifiers, it is roughly equivalent in cost because convergence coils and amplifiers are not required. It is therefore chosen as the baseline approach.

Table 11. COMPARISON OF CANDIDATE DEFLECTION APPROACHES

Parameter	Series	Parallel	Separate
Drift Requirement	0.02%	0.02%	0.02%
Expected Drift	0.50%	0.50%	0.50%
Drift Reduction Required	1/2*	1/25	1/25
Slew Voltage	218V	56V	56V
Slew Current	3A	9A	3A
Technical Risk	High	Medium	Low
Power (Horizontal Defl)	1.1	1.0	1.4
Material Cost	1.4	1.0	1.3
Reliability (Comparative MTBF)	0.6	0.85	1.0

*Since all three channels drift together, less drift reduction is required.

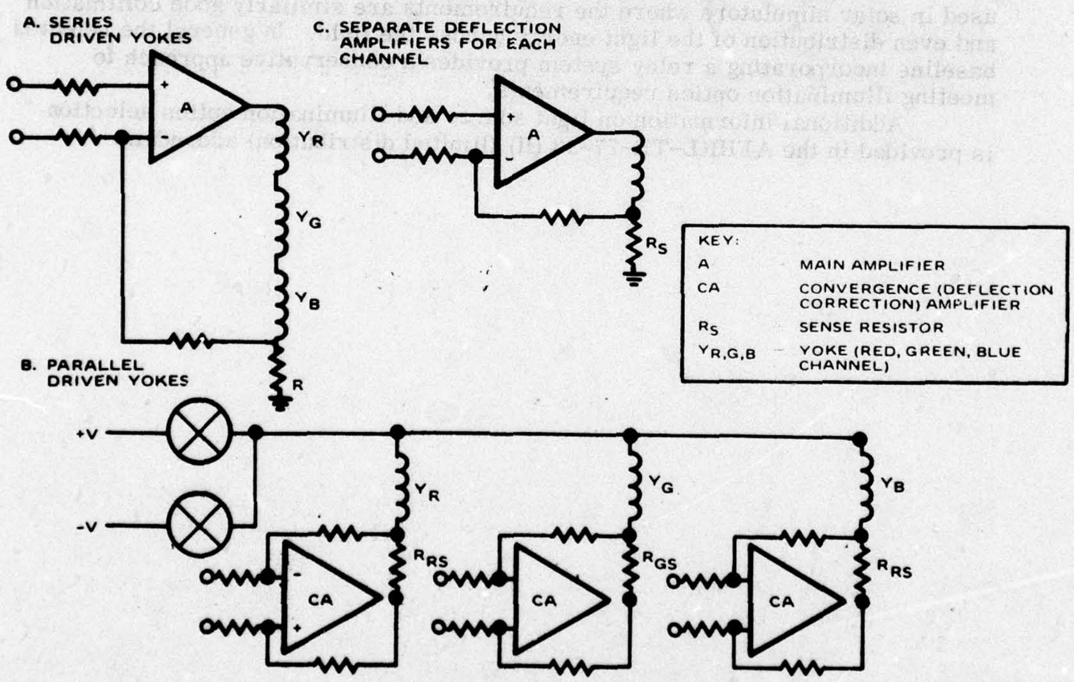


Figure 6. Approaches to Implementing the Deflection System. The series and parallel driven yoke approaches were eliminated from further consideration partly because of their high technical risk, and partly because of the need for extra hardware.

4. SELECTION OF A LIGHT SOURCE AND OPTICS FOR THE ILLUMINATION SYSTEM

Results of testing several types of light sources indicate that a suitable form of xenon arc light source is available. This is combined with suitable illumination optics which for the selected baseline is conservatively based on incorporating a relay system.

The objectives of the lamp/illumination system investigation were the tentative selection of the best lamp for the system, characterization of this lamp, and the design definition of illumination optics of high efficiency and uniform light output. Specific requirements for the illumination system/lamp combination output include a light output of 30-40,000 lumens, a beam bundle diameter of 2.2 inches, and an angle of divergence of less than ±2 degrees. (Note: A 2.2-inch-diameter beam bundle at the exit of the illumination optics is needed to provide uniform brightness coverage of the 1.8-inch LCLV image area.) All of these investigations and tests were conducted with Hughes IR&D funds; their results are utilized to support the rationale for the selected design. The baseline system requirement for 30 to 40,000 lumens, dictated the selection of a 1600 W lamp.

The 1600 W lamp was tested extensively. Test results indicate that initial light output is 39,000 lumens and that after 100 hours of operation output drops to 35,400. Beyond that, light drops at the rate of 500 lumens per 100 hours of life.

The function of the illumination optics is to collect the maximum available light out of the lamp, collimate this light into a circular 2.2-inch diameter bundle uniform to ±10%, and remove 98% of the infrared and ultraviolet radiation.

The approach selected is basically an adaptation of illumination systems used in solar simulators where the requirements are similarly good collimation and even distribution of the light energy across the field. In general the selected baseline incorporating a relay system provides a conservative approach to meeting illumination optics requirements.

Additional information on light source and illumination optics selection is provided in the AFHRL-TR-77-33 (II) (limited distribution) addendum.

5. RESULTS OF LIQUID CRYSTAL LIGHT VALVE (LCLV) TESTING

Test results on several tuned-thickness LCLV's showed good conformance to previously hypothesized LCLV performance characteristics.

The photo-activated hybrid field effect (HFE) liquid crystal light valve (LCLV) is the key element in the projector insofar as its characteristics(efficiency, response time, sensitivity, etc.) define the requirements for the remainder of the hardware. For fast response (TV cells), the LCLV uses a very thin layer of liquid crystal. For optimum contrast, the thickness of the liquid crystal must be "tuned" to the particular spectral region (color) where it will be used.

Resolution – Limiting resolution measurements were made using the standard Air Force test chart – illuminated by the fiber optic CRT. Resolution results matched expectations. 40 lp/mm is the figure used for all system calculations.

Efficiency – This number was measured at a brightness level (0.8 Bm) which yielded good resolution. Based on these measurements, 38 percent was used in subsequent system calculations/tradeoffs. The intensive on-going IR&D activity addressing this area is expected to result in improved light-efficiency and higher contrast devices in the near future.

Contrast Ratio – Measurements were initially taken using broadband (white) light producing contrast ratios which are lower than when measured under narrow spectral band conditions. The tests were repeated with a 40 nm wide filter and results substantiated the assertion that narrow-banding improves contrast. It is expected that the current liquid crystal IR&D effort will result in "tuned" light valves of appreciably improved contrast (see "Efficiency" above). Contrast ratios of 40:1 should be feasible.

Sensitivity – The CRT light output required to drive the cell to 0.8 Bm was found to be substantially what was expected (*200 fL brightness was established as an early design goal for the fiber optic CRT driving the LCLV*) and therefore matches the output capability of the CRTs developed during the study.

Response Time – Tests conducted on the light valves showed that the writeup time and decay time are nearly adequate for commercial live television, but that somewhat better response is required to fully comply with the requirement for high speed motion.

Additional information on LCLV testing is provided in the AFHRL-TR-77-33 (II) (limited distribution) addendum.

6. DICHROIC AND TRIM FILTER ANALYSIS

Selection of dichroics impacts not only color and associated parameters, but also contrast and overall projector light output. A computer program was used to analyze LCLV performance and to determine the optimum filters required to yield a good compromise between light output and color performance.

The objectives of this part of the study were to develop techniques for analyzing the spectral response of a three-color additive system which utilizes LCLVs, to perform the analysis, and to attempt to verify the results experimentally. The liquid crystal light valve is not a simple intensity modulating device; the color and intensity of the projected image change as the modulating input light is increased. The extent of the change is a function of the type of cell (thin TV cells exhibit the least color shift). Consequently the selection of the dichroics and trim filters has a critical impact not only on the range of colors that can be produced, but also on total light output, color purity, contrast and color shift with intensity modulation.

A systematic approach to analyzing the effect of spectral bandwidth for each color on the output characteristics requires a computer program. Only with the aid of the program can a variety of dichroic configurations be examined to see which one yields the best tradeoff between light output and color performance. Such a computer program was developed on IR&D to take spectral response data from light valve tests and simulate the effect of shifting the dichroic plate's transmittance spectra to shorter or longer wavelengths and the effect of using wide bandpass trim filters versus narrow bandpass trim filters. This program is explained below to provide insight to the basic optimization problem. The following topic discusses application of this program to a non-TV (CX) cell, and several TV cells.

The step-by-step analysis process performed by the computer program is shown in Figure 7. The circled numbers reference light rays shown in Figure 8 so that the actual path of the light can be traced through the system. Note that the spectral sketches are only representative. The red channel is considered in detail. (1) I_S is the "S" polarized illumination light. (2) $R_S + G_S$ is the red and green light transmitted by the blue dichroic reflector to the red and green LCLVs. The blue portion of the illumination light (not shown) is reflected to the blue LCLV. (3) R_S is the red light reflected by the red dichroic reflector. The green portion of the illumination light (not shown) is transmitted by the red reflector to the green LCLV. (4) The light reflected by the red dichroic reflector is then reflected by a second surface mirror and is directed toward the red LCLV. The second surface mirror is needed to balance the total amount of glass in each channel. Spectrally it has no effect except to slightly decrease the total amount of red light delivered to the red LCLV. (5) This figure shows that the trim filter determines the central wavelength of the red primary. It also controls the wavelengths of light that will make up the red primary and thereby controls the purity of the primary color. (6) Next the light enters the red LCLV where its axis of polarization is rotated 90° in those areas where the image occurs. This light is labeled R_P to indicate that it is red light which is now rotated to the "P" state. Also note that the optical efficiency of the LCLV has reduced the input light by ~60 percent. Where no image occurs, the axis of polarization of the light is not changed, i.e., remains R_S. The R_P and R_S light from the cell follows the same path as the incoming R_S light back to the MacNeille biprism where the light is analyzed and "S" state light is sent back to the illumination system. (7) R_P proceeds through the trim filter where it is slightly attenuated again. (8) R_P is reflected off the second surface mirror where it is again slightly attenuated. (9) R_P is reflected off the red dichroic reflector and is recombined with G_P which is transmitted by the red dichroic reflector from the green

LCLV. Gp is the light whose axis of polarization has been rotated by the green LCLV where the image occurred such that it is now "P" state. (10) Rp + Gp is transmitted by the blue dichroic reflector and combined with Bp from the blue LCLV. At this point the recombined light from the three channels enters the MacNeille biprism where only the "P" state polarized light is transmitted to the projection lens to be projected onto the projection screen. The amount of each of the primary colors (Rp, Gp and Bp) that is transmitted determines the color of the image on the projection screen which was originally generated back at the LCLVs.

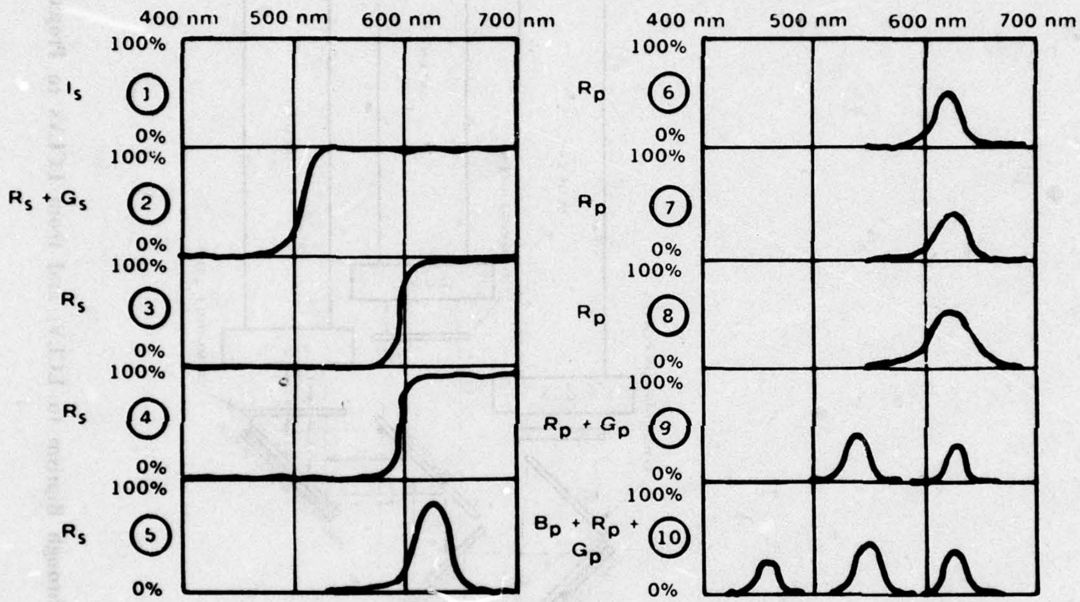


Figure 7. Step-by-Step Spectral Analysis of Light as it Passes Through the System. Circled numbers reference light ray in Figure 7.

6. DICHROIC AND TRIM FILTER ANALYSIS (Continued)

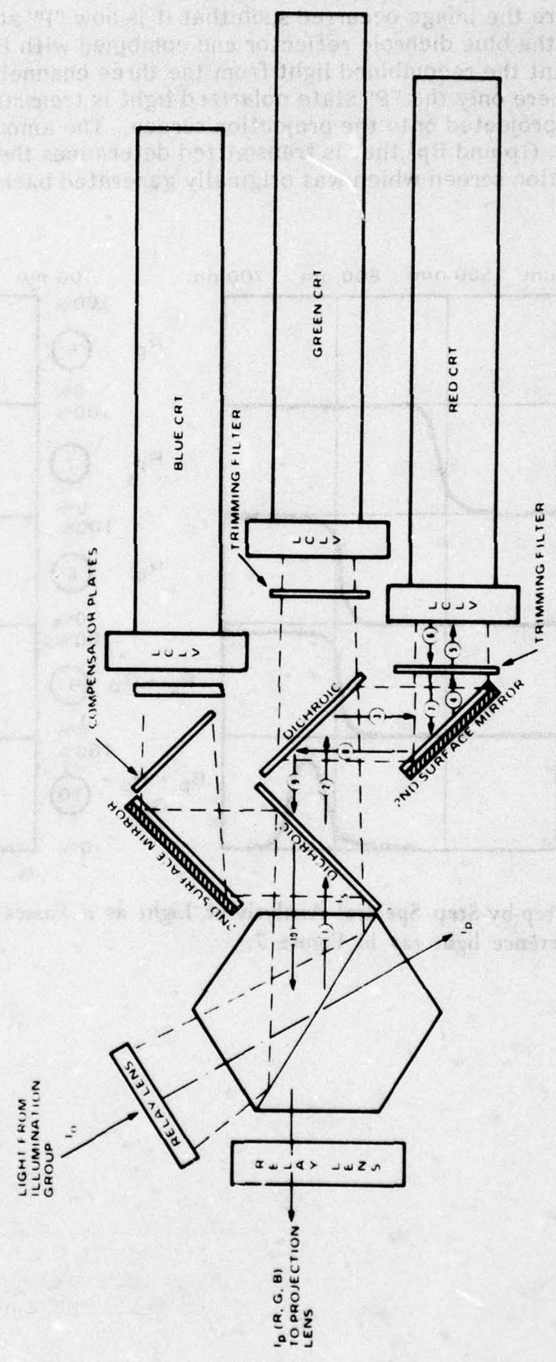


Figure 8. Path of Light Through Biprism to LCLVs and from LCLVs to Projection Lens

7. ANALYSIS OF PROJECTOR COLOR

Spectral curves derived from testing the three LCLVs were combined with filters of various bandwidths using computer modeling to arrive at the best compromise between color range, color purity and light output.

Spectral response measurements were taken on three television LCLVs; one each of the red, green and blue types. (Note: The three cells differ slightly in the thickness of the liquid crystal layer in order to maximize contrast ratio in their respective spectral bands). These tests were conducted to determine 1) the color of each channel (this allows the determination of the range of colors obtainable with a 3-channel projector), and 2) the variation in color as a function of brightness variation (this permits determining the color shift expected as image brightness is varied). Measurements were taken at different ac bias voltages across the LCLV; this procedure is equivalent to varying the input brightness into (and therefore the light reflected by) the LCLV. Using a computer program, these spectral curves were then "filtered" with filters centered around 465, 550 and 612 nm, having 50% bandwidths of 30, 40, 60 and 70 nm to calculate the CIE chromaticity diagram X and Y coordinates of the filtered output light. These coordinates were averaged for the different brightness levels, and the standard deviations in the CIE X and Y coordinates from these averages were calculated.

The range of colors obtainable with 30/40, 60 and 70 nm filters are shown with solid, dashed and dash-dotted triangles in Figure 48 (p 125), which connect these averaged (over the brightness range) coordinates. The 30 and 40 nm filter responses are very close, and are therefore treated as one. The color range of an "average" P22 phosphor (four different types exist) - are shown. The total area of the 30 and 40 nm color triangle is slightly larger than that of the average P22; however, the area is biased toward yellow, and some of the blue and red combination colors (reddish-purple through purplish-blue) cannot be generated at high saturation levels. On the other hand, the 30/40 nm filter provides a more vivid yellow and a better cyan.

The mismatch between the P22 phosphor and projector color spectrums is increased when the filter bandwidth is increased to 60 nm or to 70 nm. The line connecting red and blue rises and the attainable saturation for blue, purple and violet colors is reduced further.

Thus there is a tradeoff between color range, and light output and color constancy (as a function of brightness). As shown in Section 5, projector light output increases proportionately to filter efficiency; however, color range and color constancy are both compromised somewhat as a result.

The standard deviations from the average values of chromaticity X and Y coordinates at different brightness levels are as follows for the 30, 40, 60 and 70 nm bandwidth filters respectively (all values ±):

Blue LCLV – .004/.015, .006/.020, .010/.045, .011/.056
Green LCLV – .004/.003, .004/.004, .005/.005, .005/.005
Red LCLV – .001/.001, .002/.002, .004/.004, .005/.005

It is apparent that these deviations (which represent a shift in color) are quite small except for the 60 and 70 nm filters with the blue LCLV. Since a wider than 40 nm filter should be used with the blue LCLV to maximize brightness, some color shift will occur, the magnitude of this shift being a function of the distance of the color in question from the blue vertex of the color triangle on the chromaticity diagram. While probably discernable this shift should not adversely affect the pilot's judgment of display image quality.

8. SELECTION OF LENS TYPE

Kollmorgen was selected to perform a two-phase design study to define a high-performance, minimum cost lens because of their demonstrated competence with telecentric optical systems. The first phase of the study selected the best lens type to meet resolution and distortion requirements.

The projection lens was identified early as a critical element in the study. Not only are the basic performance parameters of the projector (light output, resolution, brightness uniformity, distortion) directly affected by the projection optics, but there was some doubt as to the basic feasibility of designing a telecentric, wide angle lens capable of projecting an appropriately distorted image onto a highly curved screen at a sufficiently high resolution to meet system requirements. Given these concerns and the long lead times required by optical designers, the analysis of the projection lens was handled as a critical path throughout the study. Special attention was devoted to maintaining good communication between the subcontractor and Hughes to speed up decision-making.

Study Approach – The basic study objective was to define a lens capable of meeting system performance requirements without having an excessively high production cost.

The approach taken to meet these objectives entailed 1) writing a detailed set of requirements for the projection optics, 2) selecting a competent vendor for the analysis/tradeoff studies, and 3) conducting the study in two phases. After the spec was written, it was given to several companies. Kollmorgen was selected on the basis of previous experience with telecentric projection lenses, and their availability of resources to commit to the study.

Phase I – The study was conducted in two phases. In Phase I, Kollmorgen investigated a variety of lens forms and configurations to arrive at one which provided the best compromise among the performance requirements of high resolution, low distortion, minimum light falloff and cost. Close coordination between Kollmorgen and Hughes was maintained in this phase to ensure compatibility with the projector as it evolved during the study.

Phase II – In Phase II, the selected lens type was subjected to detailed analysis, and was optimized with respect to performance and cost. Sensitivity analyses were performed to determine the effects of changes in magnification and prism size on performance and cost. Finally, cost data for quantities of 1, 7 and 30 were generated for the optimized lens.

A study report was generated after each phase which described, in a chronological fashion, the design process and the lens selected. A brief summary of the Kollmorgen activity is given here and in the next two topics.

Summary of Phase I – The first step in Phase I was to scrutinize the lens specifications in order to gauge the relative importance of the various requirements, and specifically to analyze the mapping transfer function of the lens. Because of the "computational display plane" approach used in the computer image generator (CIG), the lens must linearly map the LCLV image onto a plane which is tangent to the center of the hemispherical screen, and is perpendicular to the optical axis – yet the image must be focused on the curved screen, resulting (in effect) in a highly distorted image. The feasibility of changing the mapping function of the CIG was briefly considered and discarded because of its major impact on the CIG implementation.

The first problem addressed in Kollmorgen's study was the requirement for a long back focal length (BFL) (250 mm due to the prism and the dichroic assembly) and the much shorter effective focal length (EFL) which is defined by the magnification (~ 20:1) and the lens to screen distance (~ 610 mm). Thus EFL is approximately 30 mm (610/20 mm) and the ratio of back to effective focal length (BFL/EFL) is about 250 mm/30 mm = 8.3. A search of literature and patents failed to turn up high performance lens designs with BFL/EFL ratio greater than 2; a cursory analysis also confirmed the inherent impracticality of meeting the conflicting requirements of a BFL/EFL ≅ 8 on one hand, and the performance requirements on the other with a single, multi-element lens. At this point it was decided to use a set of relay lenses as the basic approach to circumvent this problem. To minimize image degradation caused by the latter, a pair of telecentric, symmetrical, 80-mm-diameter triplet lenses were used to implement the relay system. While the overall track length of the relay system is large (1200 mm), the optics may be folded without appreciable light loss, and within a reasonable volume (see Figure 9).

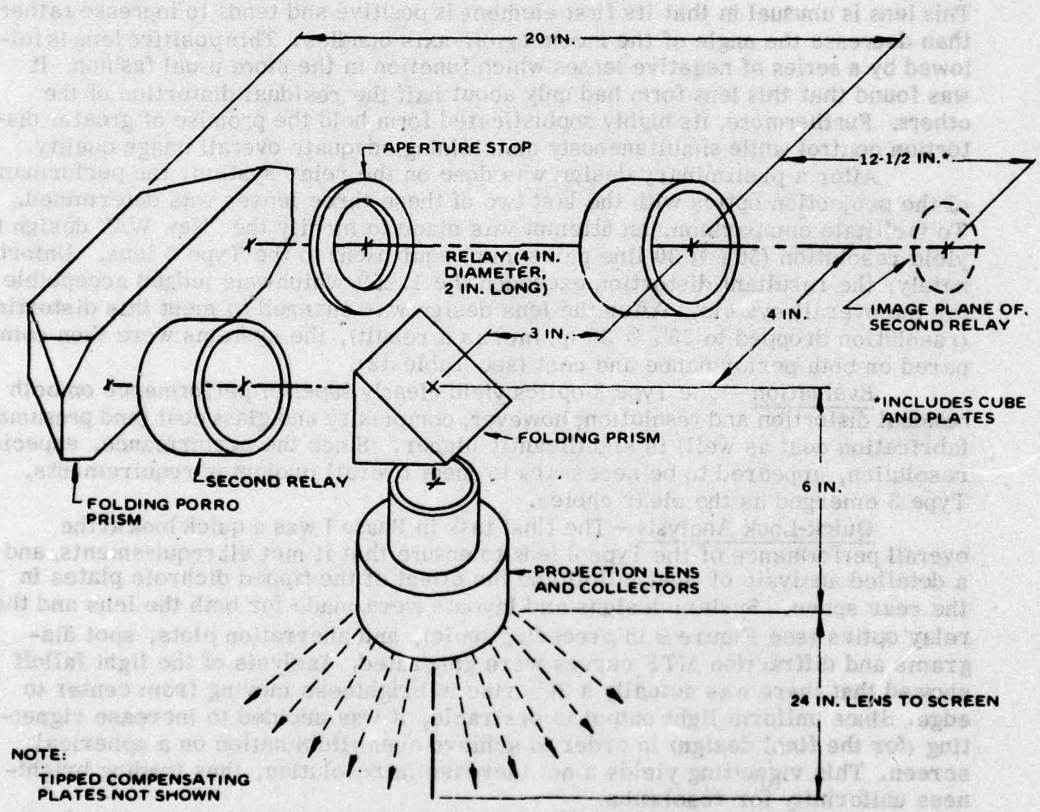


Figure 9. Folded Lens Layout. A pair of long focal length 80 mm triplets are used to relay the LCLV image to the projection lens with virtually no loss of resolution.

9. LENS FORM INVESTIGATION

Three lens configurations were investigated with the "Type 3" configuration emerging as the clear choice. This choice is based on its superior resolution and low residual distortion which override the shortcomings of its greater complexity and higher cost.

Alternative Forms – The initial cut at a feasible design is a compromise between a symmetrical lens design on one hand (best for wide angle, low distortion) and asymmetrical design optimized for telecentric light (i.e., nearly collimated light rays). This is achieved by adding positive collectors near the input surface to accommodate the near- collimated (f/8.0) input beam bundle, and simultaneously manipulating the lens form to reduce residual distortion to an acceptable level. Subsequently, a simpler (yet almost equally well-performing) version of this lens, labeled "New Wide Angle", was analyzed, and established as a candidate. Despite significant differences in size and number elements, (See A and B of Figure 10 – note difference in scale!) the two lenses exhibited roughly equivalent distortion characteristics (<3.5%) after a number of iterations which reduced the distortion of the "New WA" from 20% to 3%. To reduce distortion even further, thereby eliminating it as a source of concern, a "Type 3" lens (C of Figure 10) was investigated. This lens is unusual in that its first element is positive and tends to increase rather than decrease the angle of the incoming off-axis bundles. This positive lens is followed by a series of negative lenses which function in the more usual fashion. It was found that this lens form had only about half the residual distortion of the others. Furthermore, its highly sophisticated form held the promise of greater distortion control while simultaneously maintaining adequate overall image quality.

After a preliminary design was done on the relay system, the performance of the projection optics with the last two of these three lenses was determined. To facilitate comparison, an attempt was made to modify the "New WA" design to yield resolution (50% @ 30 line pairs/mm) equivalent to the Type 3 lens. Unfortunately, the resultant distortion exceeded the 1.25% which was judged acceptable for the overall system. After the lens design was changed to meet this distortion (resolution dropped to 35% @ 30 lp/mm as a result), the systems were then compared on both performance and cost (see Table 12).

Evaluation – The Type 3 optics yield clearly superior performance on both residual distortion and resolution; however, complexity and glass cost (and presumably fabrication cost as well) is significantly higher. Since the performance, especially resolution, appeared to be necessary to meet overall projector requirements, Type 3 emerged as the clear choice.

Quick-Look Analysis – The final task in Phase I was a quick look at the overall performance of the Type 3 lens to ensure that it met all requirements, and a detailed analysis of light falloff and the effect of the tipped dichroic plates in the rear space. System designs and layouts were made for both the lens and the relay optics (see Figure 9 in preceding topic), and aberration plots, spot diagrams and diffraction MTF curves were generated. Analysis of the light falloff showed that there was actually a 30% rise in brightness moving from center to edge. Since uniform light output is desirable, it was decided to increase vignetting (for the final design) in order to achieve even illumination on a spherical screen. This vignetting yields a net increase in resolution, thus trading brightness uniformity for resolution.

The effect of the tipped dichroic in the object space produced gross astigmatism along the horizontal axis. Two approaches to solving this problem were explored: replacing the dichroics with prisms to equalize the optical path length along both axes, and introducing a set of tipped, compensating plates around the

orthogonal axis inside the relay system. The first approach represents a formidable effort in prism design/building and is considered high risk. The second completely corrects for all astigmatism, and is the approach incorporated in the selected optics.

TABLE 12. COST/PERFORMANCE TRADEOFFS BETWEEN BEST CANDIDATE LENS FORMS

	Type 3 Objective	New WA Objective
Cost	$8500.00	$4900.00
Number of Elements	13	9
Transmission	90%	92%
Residual Distortion	0.22 mm	0.5 mm
Distortion = Zero at 17.5 mm	Yes	No
Image Quality (Avg. contrast at 30 lp/mm)	0.55	0.35
Veiling Glare	(No measurable difference)	
Assembly and Alignment Tolerances (0 = Loose, 10 = Tight)	8.0	6.0

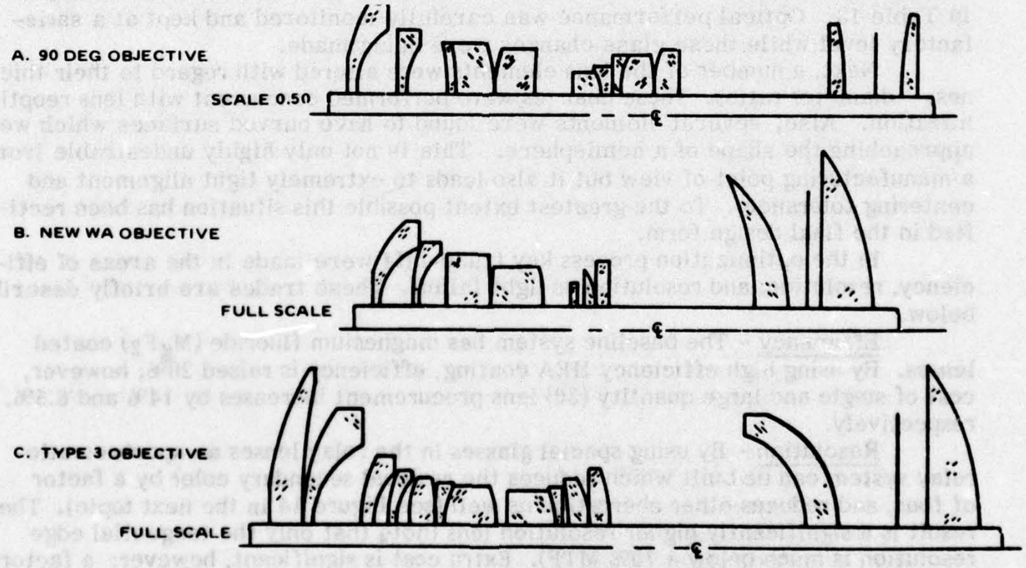


Figure 10. Three Projection Lens Forms Considered

10. OPTIMIZATION OF SELECTED PROJECTION OPTICS

Optimization of the selected Type 3 projection lens reduced manufacturing cost by approximately 40% without an appreciable degradation in performance. The result is a reasonably priced lens of remarkable performance.

Phase II of the Kollmorgen study had the objective of optimizing the lens design for manufacturability, conducting cost/performance and performance/performance trade-offs, determining sensitivity of performance to varying either image size or the size of the prism, and developing nonrecurring and recurring cost data for quantity 1, 7 or 30 units.

This effort fine-tuned the design of both relay and projection optics to account for all physical and performance constraints and to maximize performance. The manufacturability of the projection lens was then improved by reducing the number of types of glass used as well as the number of nonpreferred glass types, and by reducing the radius of curvature of some of the optical elements.

As a first step, the relay lens optics were scaled to yield an EFL of 400 mm (vs 300 mm earlier), and calculations were performed using the exact thicknesses for the rear-space dichroics, prism, and compensating tipped plates. The resulting relay system has excellent resolution limited primarily by the residual secondary axial chromatic aberration which cannot be corrected short of a major increase in the cost of the relay system. This then limits resolution of the overall projector. As the second step, the impact of increasing vignetting to reduce the light increase at the edge of the screen was examined. Since a significant resolution improvement was realized, it was decided to incorporate vignetting into the baseline system.

Examining the "feasibility configuration" of the projection lens, several areas were found where modifications could make the lens more producible. First, the choice of glass types was carefully reviewed. Material cost, availability, and workability were considered in detail. The results of this review are summarized in Table 13. Optical performance was carefully monitored and kept at a satisfactory level while these glass changes were being made.

Next, a number of the lens elements were altered with regard to their thickness – diameter ratios. These changes were performed concurrent with lens reoptimization. Also, several elements were found to have curved surfaces which were approaching the shape of a hemisphere. This is not only highly undesirable from a manufacturing point of view but it also leads to extremely tight alignment and centering tolerances. To the greatest extent possible this situation has been rectified in the final design form.

In the optimization process key trade-offs were made in the areas of efficiency, resolution, and resolution vs light falloff. These trades are briefly described below.

<u>Efficiency</u> – The baseline system has magnesium fluoride (M_gF_2) coated lenses. By using high efficiency HEA coating, efficiency is raised 20%; however, cost of single and large quantity (30) lens procurement increases by 14% and 6.5%, respectively.

<u>Resolution</u> – By using special glasses in the relay lenses an apochromatic relay system can be built which reduces the residual secondary color by a factor of four, and reduces other aberration as well (see Figure 14 in the next topic). The result is a significantly higher resolution lens (note that only the tangential edge resolution is much below a 70% MTF). Extra cost is significant, however: a factor of 1.19 and 1.17 for a quantity one and thirty procurement respectively, due to both increased cost of glass and higher tolerances.

Resolution vs Light Falloff – Light falloff can be changed (to 130%) to help to minimize overall projector light falloff; i.e., by compensating for light falloff in the illumination optics. However, resolution suffers – the MTF at 30 lp/mm drops from 40% to 25%. The selected baseline appears to be the best design.

TABLE 13. PROJECTION LENS SIMPLIFICATION

	Feasibility Design	Final Design
Number of Glass Types Used	9	6
Relative Material Cost	100	57
Relative Cost of Manufacture	100	75
Blanks of Nonpreferred* Glass Types	7	3

*With regard to availability and delivery schedules.

11. PERFORMANCE OF OPTIMIZED PROJECTION OPTICS

Performance of the optimized baseline lens/relay combination exceeds expectations in all areas but efficiency. Options are available to further increase performance if the increased cost is justifiable.

The performance of the projection lens/relay combination is presented in Table 14 and in Figures 11 through 14 showing MTF (center/edge, tangential/saggital spot size), distortion characteristics, and ray aberration plots.

The numbers in the table under the Baseline Lens (M_gF_2 coating) column substantiate the claim for excellent performance. Distortion and resolution goals have been satisfactorily met, and light falloff is significantly better than was originally expected. Veiling glare (contrast) was not analyzed in detail, but is estimated to be less than 0.5%. The only area where performance fell short of expectations is efficiency. The basic problem here is the large number of glass surfaces the light must travel through. The numbers in the growth column reflect alternatives identified in the optimization tradeoff studies that could be incorporated at additional cost if required.

Sensitivity Analyses – The final lens design was analyzed for sensitivity to changes in magnification, and change in size of the polarizing prism. It was found that a 20% reduction in LCLV image size (i.e., magnification changes from 19.8X to 26.6X) results in no degradation in resolution, but greatly increases distortion; however, a lens initially designed for a different magnification would have roughly the same performance as the baseline lens.

Changing the prism size (reducing by 10% to 30%) has no perceptible effect on performance .

Cost Data – Recurring and non-recurring costs (from Kollmorgen to Hughes) were developed for procurement of 1, 7 and 30 lenses. Basic vendor lens cost (low efficiency, standard relay) is $36,020, for the first one (plus a $39,200 non-recurring cost), and $11,000 in quantities of thirty. Although the lens is an expensive item, its cost is quite reasonable considering the high level of performance obtained.

TABLE 14. PROJECTION OPTICS PERFORMANCE CHARACTERISTICS

	Baseline Lens	Growth	Comments
Efficiency	49%	59%	Cost increase of 6.5% to 14%
Distortion			
Center at 0.4R (max)	0.22 mm (0.6%)	Same	
at 1.0R	0	Same	
Resolution (MTF @ 30 lp/mm)*			
Tangential center	0.45	0.75	Improvement with apochromatic relay. Cost increase of 18%
Tangential edge	0.40	0.52	
Sagittal center	0.45	0.76	
Sagittal edge	0.40	0.76	
Glare (veiling)	0.5%	Same	Estimated (no analysis performed)
Light Falloff	±5%	Same	Tradeoff for increased resolution
Spectral Range	Visual	Same	
Magnification	20X	Same	

*1200 lp/display height equivalent

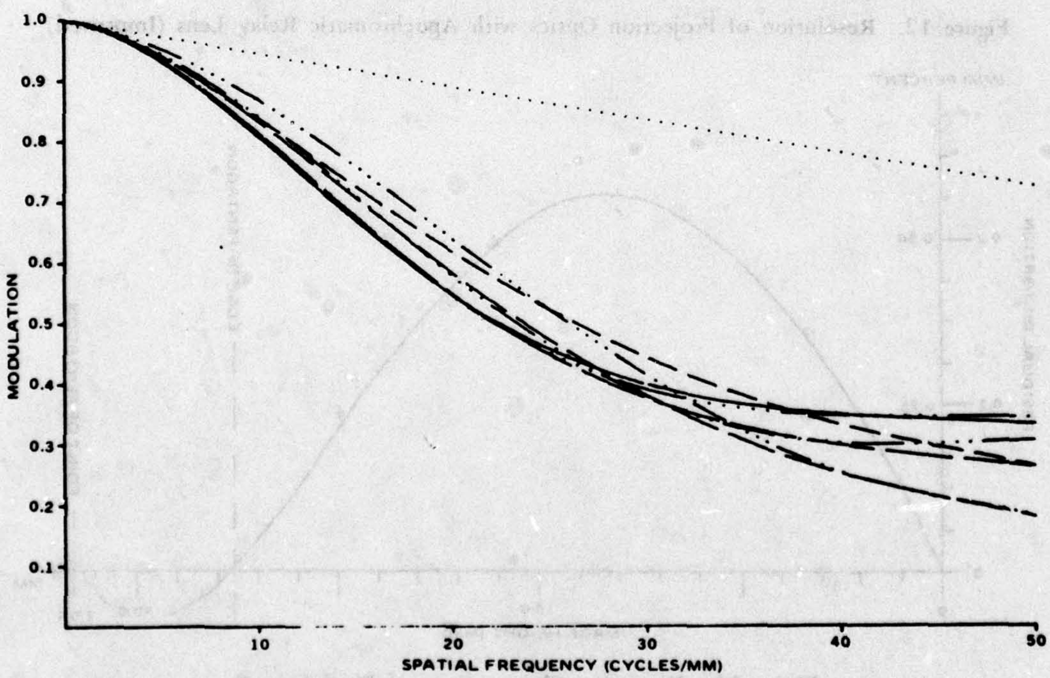


Figure 11. Resolution of Projection Optics with Conventional Relay Lenses (Baseline)

11. PERFORMANCE OF OPTIMIZED PROJECTION OPTICS (Continued)

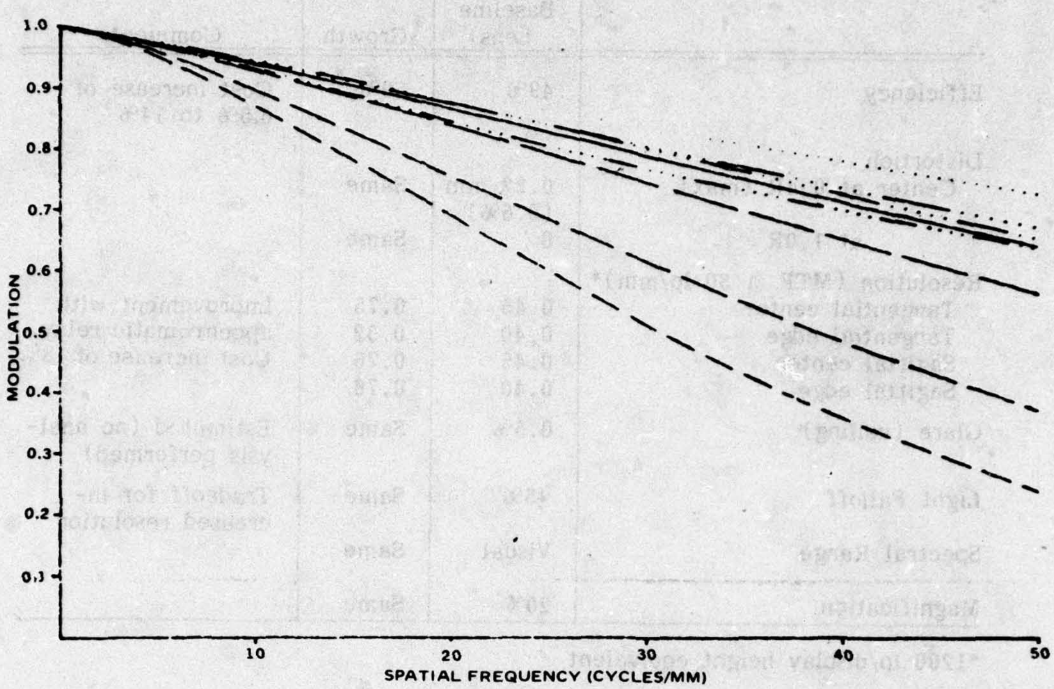


Figure 12. Resolution of Projection Optics with Apochromatic Relay Lens (Improved)

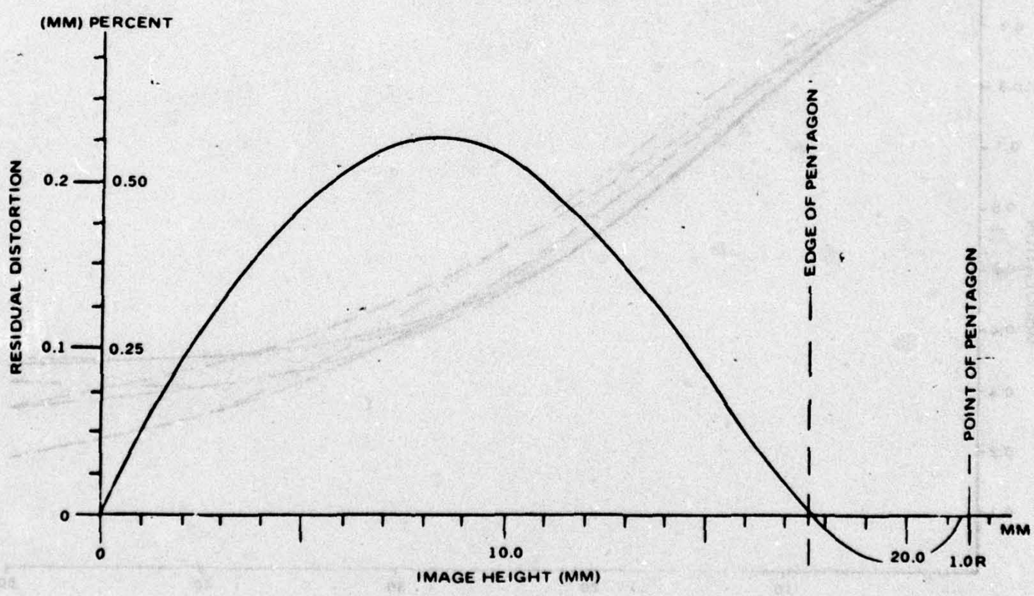


Figure 13. Distortion Characteristic of Final Lens Form

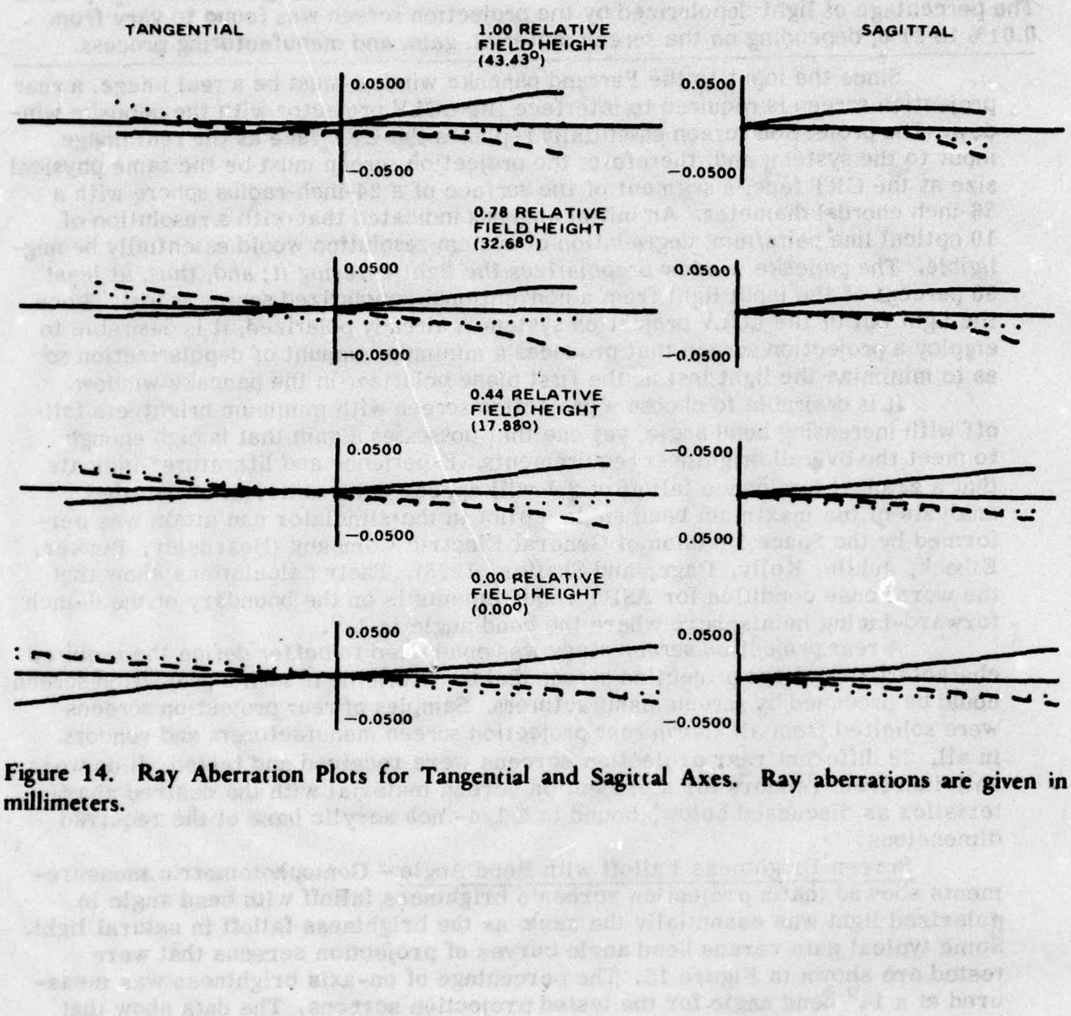


Figure 14. Ray Aberration Plots for Tangential and Sagittal Axes. Ray aberrations are given in millimeters.

12. RESULTS OF THE SCREEN TESTS

The screen tests indicate that a projection screen with a gain of 8 will provide the required brightness and that the brightness falloff at a 14° bend angle will be acceptable. The percentage of light depolarized by the projection screen was found to vary from 0.01% to 21%, depending on the screen material, gain, and manufacturing process.

Since the input to the Farrand pancake window must be a real image, a rear projection screen is required to interface the LCLV projector with the pancake window. The projection screen essentially replaces the CRT face as the real image input to the system; and, therefore, the projection screen must be the same physical size as the CRT face, a segment of the surface of a 24-inch-radius sphere with a 36-inch chordal diameter. An initial analysis indicated that with a resolution of 10 optical line pairs/mm, degradation of system resolution would essentially be negligible. The pancake window prepolarizes the light entering it; and, thus, at least 50 percent of the input light from a conventional unpolarized source is lost. Since the light out of the LCLV projection system is already polarized, it is desirable to employ a projection screen that produces a minimum amount of depolarization so as to minimize the light lost at the first plane polarizer in the pancake window.

It is desirable to choose a projection screen with minimum brightness falloff with increasing bend angle, yet one that possesses a gain that is high enough to meet the overall brightness requirements. Experience and literature* indicate that a gradual luminance falloff of 2:1 will appear quite uniform. A detailed analysis of the maximum bend angle a pilot in the simulator can attain was performed by the Space Division of General Electric Company (Beardsley, Bunker, Eibeck, Juhlin, Kelly, Page, and Shaffer, 1975). Their calculations show that the worst case condition for ASPT requirements is on the boundary of the 6-inch forward-facing hemisphere where the bend angle is 14°.

A rear projection screen study was conducted to better define the required characteristics of the projection screen and to determine if such a projection screen could be produced by screen manufacturers. Samples of rear projection screens were solicited from all known rear projection screen manufacturers and vendors. In all, 28 different rear projection screens were received and tested. Bids were solicited from vendors for a projection screen material with the desired characteristics as discussed below, bound to a 1/4-inch acrylic base of the required dimensions.

Screen Brightness Falloff with Bend Angle – Goniophotometric measurements showed that a projection screen's brightness falloff with bend angle in polarized light was essentially the same as the brightness falloff in natural light. Some typical gain versus bend angle curves of projection screens that were tested are shown in Figure 15. The percentage of on-axis brightness was measured at a 14° bend angle for the tested projection screens. The data show that even a screen with a gain of 10 will only produce little more than a 2:1 falloff at a 14° bend angle.

Screen Depolarization Factor – The amount of light depolarized by a particular projection screen was measured by testing it in a conventional projection light that was prepolarized and by using a rotatable linear polarizer at the aperture of the measuring photometer. The amount of depolarization incurred varied with screen gain and with the manufacturing process. It was found that the percentage of depolarization typically decreased with increasing screen gain.

*H. R. Luxenburg and Rudolph L. Kuehn, Display Systems Engineering (New York, 1968), p. 297.

Screen Resolving Power – The limiting resolution of the screen samples varied from 7 line pairs/mm to 228 + line pairs/mm. Projection screens with gains of 7 or 8 can easily be obtained with 14 to 16 line pairs/mm resolution. Thus, the projection screen will not effectively influence the overall system resolution performance.

Other Areas – No testing was performed on screen uniformity or on screen contrast for curved, high gain screens. While the GE study (ref. Beardsley et al., 1975) showed significant variations over the screen, at least one supplier claims competence in providing screens of both high gain and very high (<5%) uniformity. It was therefore assumed that the contribution of screen gain variation to overall system uniformity will be negligible.

Because of the high gain, loss of contrast on the screen (though it is curved) should be negligible. However, no experimental data were generated on the study to support this statement. In the study conducted by GE (ref. Beardsley et al., 1975, p 235), a curved LS85 gain of 15 was tested; contrast ratios were found to be in excess of 500. Since the geometry of light scattering contrast appears to increase with gain, a lower gain (e.g., light) should have somewhat lower, but still very high, contrast. A contrast ratio of 250 would therefore appear to be reasonable.

Cost Data – To verify cost feasibility, vendor quotes were obtained for a curved screen with a gain of 7 (this gain appeared to be a reasonable forecast of final selection at the time the inquiries were conducted). In general, all vendor prices were roughly equivalent.

Conclusion – The screen investigation and testing has shown that a suitable screen having very acceptable parameters can readily be procured. Such a screen will have a depolarization factor of approximately 5 percent, resulting in only 5 percent loss of light due to the first polarizer in the pancake window. The expected resolving power of an 8-gain projection screen is from 13 to 18 line pairs/mm; the effect on system resolution will therefore be negligible.

Additional information on screen test results is provided in the AFHRL-TR-77-33 (II) (limited distribution) addendum.

12. RESULTS OF THE SCREEN TESTS (Continued)

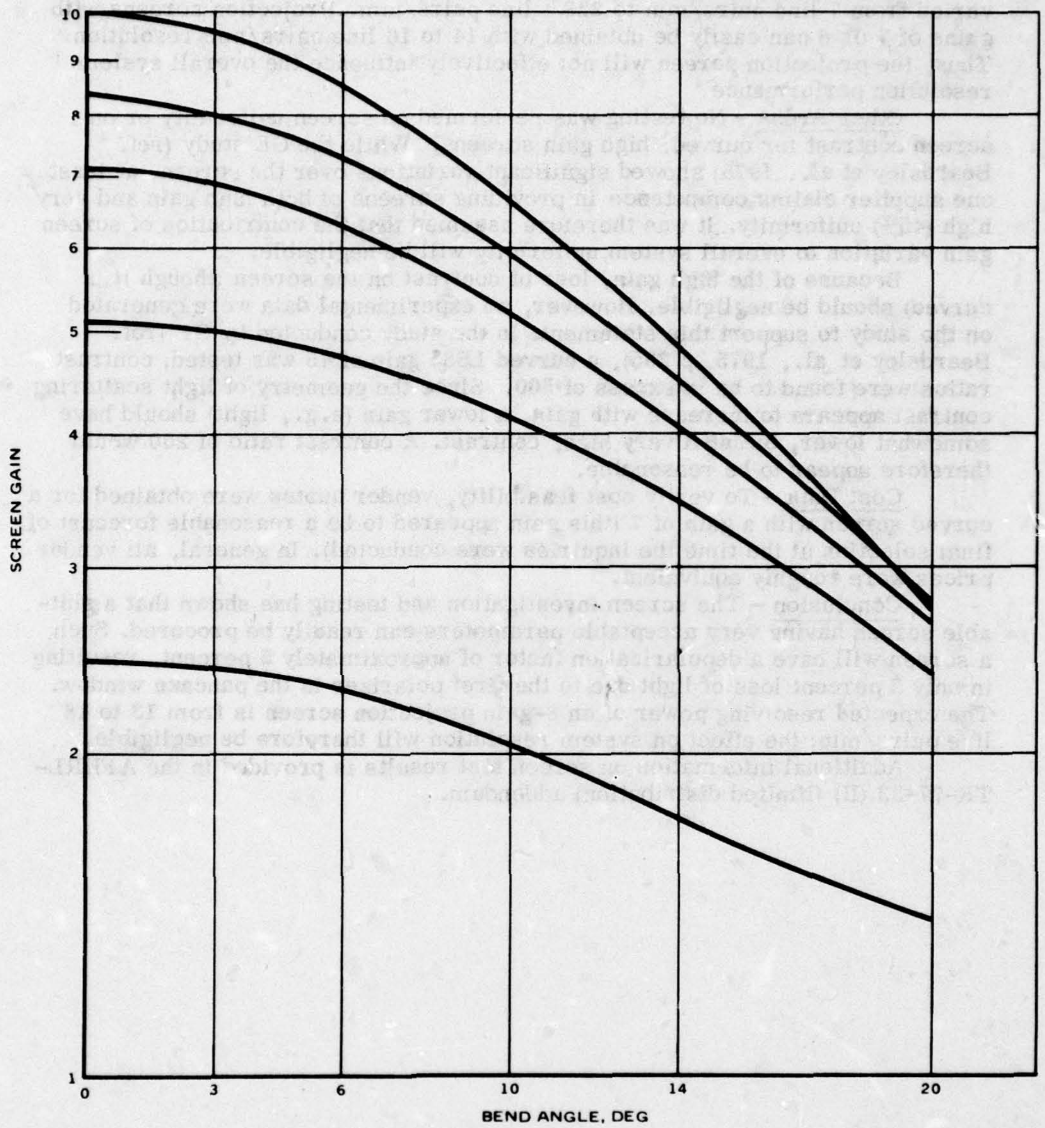


Figure 15. Goniophotometric Plot of Some Typical Rear Projection Screens of Various Gains Using a Linearly Polarized Projection Light Source. A screen with even a gain of 10 will produce only about 2:1 falloff at a 14° bend angle.

SECTION 5
SYSTEM TRADE-OFFS

1. PROJECTOR LIGHT OUTPUT TRADE-OFFS – AVAILABLE OPTIONS

Component parameters identified in the component investigations phase are used as the available alternatives for optimizing light output.

Brightness is one of the most important system parameters, both from an operational point of view on the one hand, and from an equipment size, weight, power and cost on the other. At the same time it is also the most complex one to analyze because it is affected by so many system components. A special effort was made in the study to explore all feasible alternatives affecting screen brightness, in order to end up with the best combination of technical feasibility/low risk, and performance. The options available are summarized in Table 15.

The following approach was taken to streamline the tradeoff analysis. We separated output screen brightness (B) into its two components: projector light output (L_o), and the effective screen gain (G_{eff}). (Note: "effective" screen gain accounts for the polarization in the screen.) The relationship between these parameters is defined by the equation $B = L_o \times G_{eff}/A$, where A is the screen area (which is fixed at 6.75 square feet). Thus screen brightness is proportional to both L_o and G_{eff}. This topic and the next discuss the options available for L_o, while the one after examines the impact of choosing the value of screen gain on light falloff with pilot head motion, a rather complex issue. Finally, three alternative optimized system configurations are discussed in the fourth topic, and one of these is selected as the baseline.

Light Output Model – The components which contribute to determining projector light output are shown in Figure 16. The numbers shown for each component are those values of efficiency which were found to be reasonable alternatives based on the individual component investigations (Section 4). These are briefly summarized here for the reader's convenience. Three sealed beam structure lamps (1.0 kW, 1.6 kW, 2.5 kW) with light outputs proportional to input power are potential light sources; however, since the 2.5 kW size has not been tested as yet, using it entails performance risk (i.e., can it deliver a proportionate share of the light it generates to the LCLV image plane?). The illumination system can be implemented with a relay (22%) or without one (29%). The latter is both more efficient and smaller but has not as yet been reduced to practice. The dichroics can be configured to yield a very large variety of filter combinations; of these, three were selected as reasonable alternatives: narrow band dichroics – with filter bandwidth of 30 nm, and relatively low efficiency (14.5%) with an output which is compatible with the trichromatic holographic pancake window (Type I); full color-range dichroics of slightly higher efficiency (29%) which have a slight color-shift of intensity (Type II); and high efficiency (35 + %) dichroics which sacrifice color purity and the capability to display a CIE illuminant C white to maximize efficiency.

The measurements on the LCLV indicate an efficiency of 38%. It is expected, however, that the continued improvements in the light valve will result in significant improvements, with an efficiency of 60% being a reasonable upper limit. Beam splitter efficiency is fixed at 45%; no changes are expected. Finally, the projection optics can be built without and with high efficiency HEA coating to yield efficiencies of 49% and 59%, respectively.

Table 15. SUMMARY OF OPTIONS AVAILABLE

Element	Option	η/Lumens
Lamp Module	1,000 W	22,000
	1,600 W	35,400
	2,500 W	55,500
Illumination System	With Relay	22%
	No Relay	29%
Dichroics	Type I	14.5%
	Type II	29%
	Type III	35%
LCLV	Current (measured)	38%
	Expected	60%
Projection Optics	MgF2 Lens Coating	49%
	HEA Lens Coating	59%

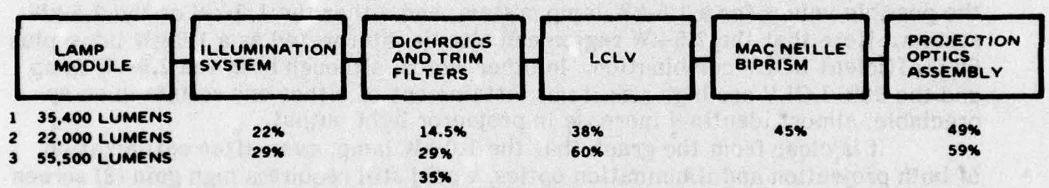


Figure 16. Model for Calculating Projector Brightness. These individual elements are completely independent of each other and can be combined in different ways to provide different levels of performance. Performance options are listed below each element block.

2. PROJECTOR LIGHT OUTPUT TRADE-OFFS – COMPARISON OF CANDIDATES

Parametric curves show the range of values attainable with the baseline projector. A 1.6-kW lamp with no relay system is the best choice, with the projection optics efficiency traded off for screen gain in the next topic.

Since the components involved in determining projector light output are completely independent of each other, they may be combined in a number of different ways (3 x 2 x 3 x 2 x 1 x 2 = 72) to yield a wide range of performance levels.

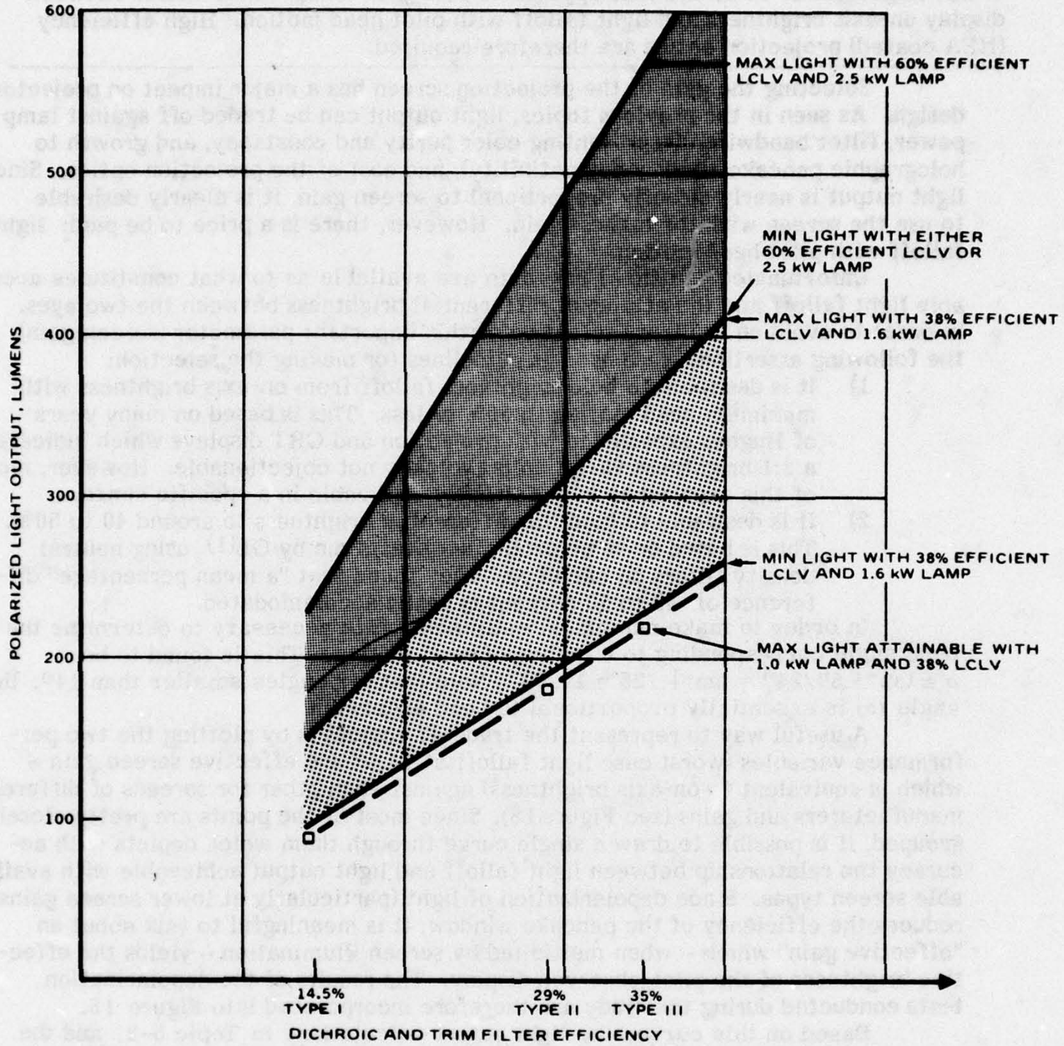
To make the analysis manageable, those options which represent medium to high risk were first eliminated. Specifically, the currently measured value for light valve efficiency is 38%; while continued improvement of the LCLV as a result of ongoing IR&D will certainly raise this toward the eventually likely value of 60%, prudence indicates use of the 38% figure at this time. Similarly, the fact that the 2.5-kW lamp has not as yet been tested makes its use risky; it should not be considered unless higher light output is an absolute must.

Next, the remaining options were plotted on a two-dimensional graph with the abscissa being the efficiency of the dichroic set (the latter has the largest number of options – three – and is most easily changed by selecting a different dichroic/trim filter combination), and the ordinate being the light output (Figure 17). The maximum and minimum values for systems with a 1.6-kW lamp source are drawn as a function of dichroics efficiency; the shaded area between these lines represents possible light levels obtainable by proper selection of the right illumination and projection optics.

To determine light output with other lamps, similar boundaries were drawn for the 1.0 kW and 2.5 kW. Interestingly, there is essentially no overlap between the possible values for a 1.6-kW lamp system, and either the 1.0-kW or the 2.5-kW system. Note that the 2.5-kW region can also be interpreted as a 1.6-kW lamp plus 60%-efficient LCLV combination. In other words, although both the 2.5-kW lamp and the 60% LCLV are high risk items, attainment of either one results in an appreciable, almost identical increase in projector light output.

It is clear from the graph that the 1.0-kW lamp, even after optimization of both projection and illumination optics, would still require a high gain (8) screen to meet brightness requirements. It is therefore judged inadequate, and not considered further.

In conclusion, the 1.6-kW appears the best lamp choice. Selection of the higher efficiency illumination optics is somewhat risky, and is therefore not recommended. The decision therefore reduces to whether to use a high (9.1) or lower (7.6) gain screen, and whether to use the 59% or 49% efficiency projection optics. To make this decision requires considering system parameters other than just light output; these other areas are considered in the next topic.



TYPE I. 30 nm FOR TRICHROMATIC HOLOGRAPHIC PANCAKE WINDOW

TYPE II. NO TRIM FILTER IN BLUE CHANNEL, ~ 60 nm F.W.H.M. FILTERS IN RED AND GREEN CHANNELS (BASELINE)

TYPE III. UNBALANCED PRIMARIES (WHITE SHIFTED TOWARD GREEN AND RED PRIMARIES)

Figure 17. Light Output versus Filter Bandwidth for Projector. The shaded area between the lines represents possible light levels obtainable by proper selection of illumination and projection optics.

80

3. TRADING OFF BRIGHTNESS AND LIGHT FALLOFF

A screen with a gain of 8 yields a worst case light falloff of only 44% and a differential brightness of 50%, and thus appears to be a good compromise choice between display on-axis brightness and light falloff with pilot head motion. High efficiency (HEA coated) projection optics are therefore required.

Selecting the gain of the projection screen has a major impact on projector design. As seen in the previous topics, light output can be traded off against lamp power, filter bandwidth (representing color purity and constancy, and growth to holographic pancake window compatibility), and cost of the projection optics. Since light output is nearly directly proportional to screen gain, it is clearly desirable to use the screen with the highest gain. However, there is a price to be paid: light falloff with pilot head motion.

Unfortunately, little (if any) data are available as to what constitutes acceptable light falloff and the attendant differential brightness between the two eyes. In order to avoid an arbitrary selection of this important parameter (screen gain), the following assertions were used as guidelines for making the selection:

1) It is desirable to hold brightness falloff from on-axis brightness with maximum head motion to 50% or less. This is based on many years of Hughes experience with projection and CRT displays which indicates a 2:1 brightness variation is typically not objectionable. However, most of this experience is not directly applicable in a specific sense.
2) It is desirable to hold the differential brightness to around 40 to 50%. This is based on some preliminary tests run by GE[1] using neutral density filters on each eye. They found that "a mean percentage" difference of 40 to 50 percent is easily accommodated.

In order to make numerical estimates, it is necessary to determine the bend angle corresponding to 6 inches of head motion. This is found to be $\alpha \cong \tan^{-1} 6''/24'' = \tan^{-1} .25 = 14.0^o$. Note that for angles smaller than 14^o, the angle (α) is essentially proportional to head excursion.

A useful way to represent the tradeoff choices is by plotting the two performance variables (worst case light falloff at 14.0^o and effective screen gain – which is equivalent to on-axis brightness) against each other for screens of different manufacturers and gains (see Figure 18). Since most of the points are pretty closely grouped, it is possible to draw a single curve through them which depicts with accuracy the relationship between light falloff and light output achievable with available screen types. Since depolarization of light (particularly at lower screen gains) reduces the efficiency of the pancake window, it is meaningful to talk about an "effective gain" which – when multiplied by screen illumination – yields the effective brightness of the pilot-observed display. The results of the depolarization tests conducted during the study are therefore incorporated into Figure 18.

Based on this curve, the light output calculations in Topic 5-2, and the formula $B = L_o \times G_{eff}$, it appears that both gains of 7.6 (with high efficiency, HEA coated projection optics) and 9.1 (without high-efficiency coating) are reasonable. To use practical screens, and to provide a margin of safety, screens with gains of 8 and 10 were used. To determine which of these is acceptable requires consideration of both the light falloff averaged for both eyes, and a check on differential brightness.

Both of these parameters are plotted for both the 8 and 10-gain screens as a function of head position in Figures 19 and 20. It appears that the 8-gain screen

---

(1) Beardsley et al. (1975).

meets both criteria set up above: average brightness is off less than 50% (45%), and differential brightness is exactly 50%. The 10-gain screen is somewhat worse, and falls below the required values. The 8-gain screen is thus the logical selection for the baseline system.

It is worth noting that since the pilot will move his head more than 4 inches only infrequently, average light falloff ($1 - B_R$) and differential brightness for this screen gain will not generally exceed 25% and 40%, respectively.

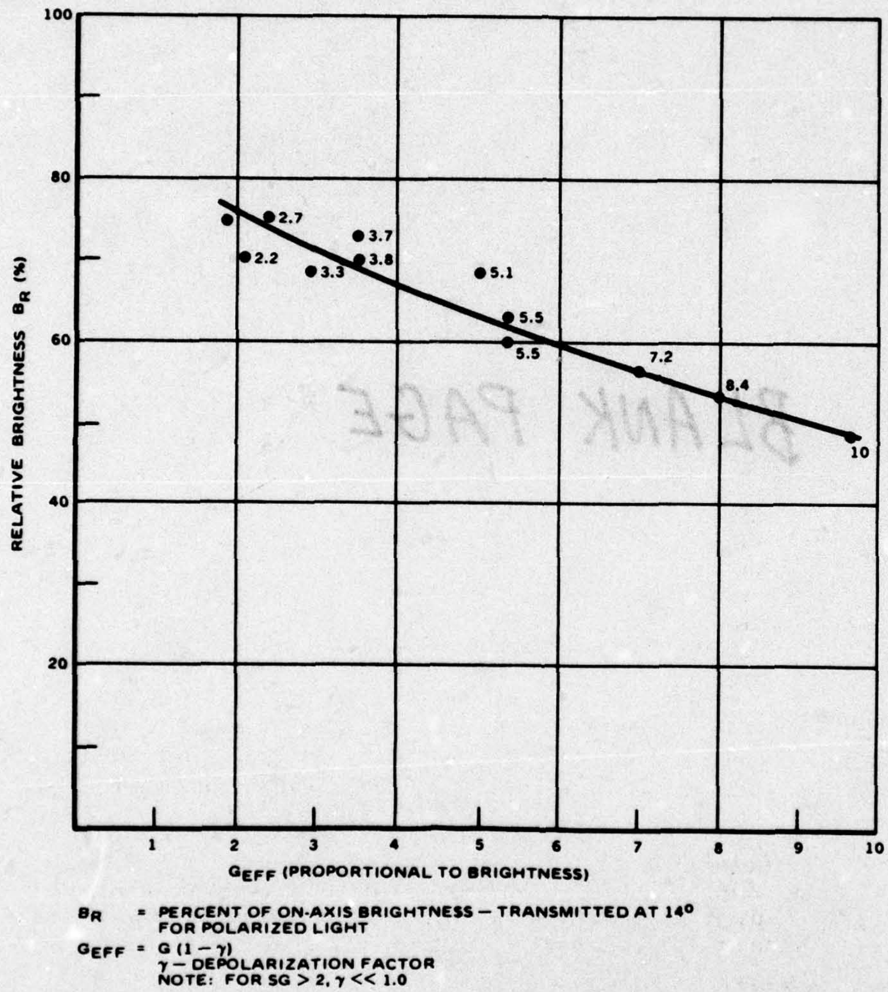


Figure 18. Relative Brightness (B_R) at Maximum (6") Pilot Head Motion. Light falloff ($1 - B_R$) at 14° – corresponding to 6" head motion – can be traded off against brightness at nominal head position by choosing screens of different gain.

Preceding Page Blank - NOT Filmed

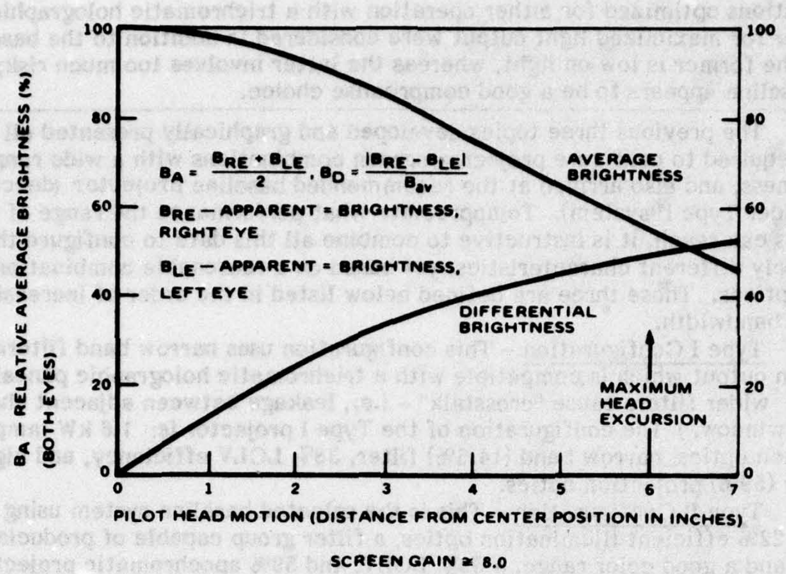


Figure 19. Relative Average and Differential Brightness versus Pilot Head Motion for a Screen Gain of 8

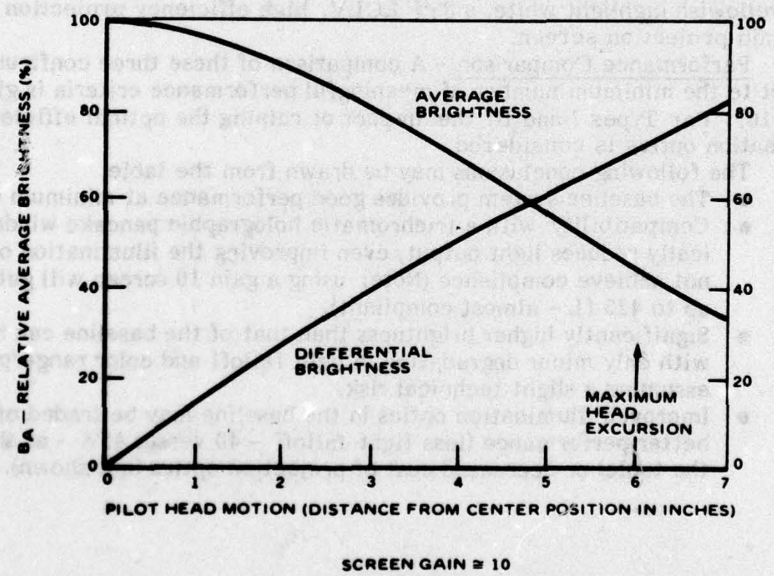


Figure 20. Relative Average and Differential Brightness versus Pilot Head Motion for a Screen Gain of 10

4. COMPARISON OF THREE "REASONABLE" PROJECTOR CONFIGURATIONS

Configurations optimized for either operation with a trichromatic holographic pancake window, or for maximized light output were considered in addition to the baseline projector. The former is low on light, whereas the latter involves too much risk; the selected baseline appears to be a good compromise choice.

The previous three topics developed and graphically presented all of the data required to configure projector/screen combinations with a wide range of brightness, and also arrived at the recommended baseline projector (described below under Type II system). To appreciate what performance the range of available options can reach, it is instructive to combine all this data to configure three systems of widely different characteristics, yet based on a reasonable combination of available options. These three are defined below listed in the order of increasing dichroic filter bandwidth.

Type I Configuration – This configuration uses narrow band filters to generate an output which is compatible with a trichromatic holographic pancake window. (Note: wider filters cause "crosstalk" – i.e., leakage between adjacent channels – in the window.) The configuration of the Type I projector is: 1.6 kW lamp, 22% illumination optics, narrow band (14.5%) filter, 38% LCLV efficiency, and high efficiency (59%) projection optics.

Type II Configuration – This is the selected baseline system using a 1.6 kW lamp, 22% efficient illumination optics, a filter group capable of producing a good white and a good color range, a 38% LCLV, and 59% apochromatic projector optics.

Type III Configuration – This projector is configured for maximum light output, at the expense of some risk and color purity. The configuration incorporates a 1.6 kW lamp, high efficiency (29%) illumination optics (at some risk, since its availability depends on development of an elliptical lamp reflector which can be optimized to eliminate the relay optics), wide band dichroics which produce a somewhat yellowish highlight white, a 38% LCLV, high efficiency projection optics, and a 10-gain projection screen.

Performance Comparison – A comparison of these three configurations with respect to the minimum number of meaningful performance criteria is given in Table 16. For Types I and II, the impact of raising the optical efficiency of the illumination optics is considered.

The following conclusions may be drawn from the table:

- The baseline system provides good performance at minimum risk.
- Compatibility with a trichromatic holographic pancake window dramatically reduces light output; even improving the illumination optics does not achieve compliance (Note: using a gain 10 screen will get brightness up to 425 fL – almost compliant).
- Significantly higher brightness than that of the baseline can be achieved with only minor degradation in light falloff and color range/purity, by assuming a slight technical risk.
- Improved illumination optics in the baseline may be traded off against better performance (less light falloff – 40 versus 45% – as shown in the table) or decreased cost of projection optics (not shown).

TABLE 16. COMPARISON OF THREE REASONABLE PROJECTOR CONFIGURATIONS

	Type I	Type II	Type III
Description	**Compatible with Trichromatic Holographic Pancake Window**	**Baseline System (compliant, minimum risk)**	**High-Brightness Projector**
Brightness (effective)	**225 (340*) fL**	**510 fL**	**1010 fL**
Light Falloff(1)	**45%**	**45% (40%*)**	**53%**
Color Range	**Good**	**Fair**	**Acceptable(2)**
Color Purity	**Excellent**	**Fair**	**Acceptable**

***With improved illumination optics (elliptical lamp reflector)**
(1) With pilot head motion of 6 inches
(2) "White" has yellowish tinge

5. SYSTEM-LEVEL RESOLUTION TRADE-OFFS

The least-risk approach to meeting the center resolution requirement of 30% MTF at 1000 TVL is a video bandwidth of 30 MHz, an LCLV resolution of 40 lp/mm, a CRT spot size of 1.1 mils, and the use of apochromatic relay lenses in the projection optics.

The prime objective of this study, the design of a color visual simulation projection system, includes the quantitative determination of an "optimum resolution" system. Optimization of system resolution must be accompanied by consideration of the risk involved as well as the cost for each component. In Topic 7-6 a series-string model is described which shows the system components that determine system resolution. The system components in that model are discussed here in terms of the range of performance available for the resolution-defining parameter.

Video Bandwidth – The bandwidth of the video chain depends on the cascaded bandwidth of three elements: the preamplifier, the gamma-correction circuit, and the video amplifier. A two-pole slightly peaked video response which meets the design requirement of ±1 dB at 20 MHz, and has a 3 dB response at 30 MHz, implies a bandwidth of at least 50 MHz in each element. This is state-of-the-art, and further significant improvements, while feasible, may not be cost-effective (particularly for the gamma correction circuit). A 30 MHz bandwidth is therefore selected as the baseline.

Note that the persistence of the LCLV somewhat alleviates the problem of increasing bandwidth. Higher bandwidth typically means decreased signal-to-noise ratio. However, the LCLV integrates the noise, granting a degree of freedom in the design of the amplifier not present with conventional display phosphors.

It should also be noted that if the CIG output is digital, gamma correction can be implemented digitally, and a video channel bandwidth of 50 MHz should be readily attainable.

CRT Spot Size – A CRT spot size (at 50%) of 1.3 mils has been demonstrated, and a spot size of 1.1 mils at 200 footlamberts using 15 kV appears readily obtainable. The results from further research and development work should permit a decrease in spot size to 0.9 mils. Although cost is not a prime consideration, some technical risk is associated with the latter reduction in spot size.

LCLV – The limiting resolution of several different cells was measured and found to be typically 40 lp/mm. As there is continual development being carried out in this area, it is reasonable to expect an increase to 50 lp/mm in the near future.

Optics – The Kollmorgen study concluded that with a conventional relay, an MTF of 80% at 1000 lines was achievable. Using apochromatic relay lenses produces a 15% increase in center MTF, at a substantial increase in cost.

Image Size – With a 1.8-in. diameter LCLV, 1.6 in. is the resultant mage size. Increasing the size of the image through the system is an obvious means of improving each component resolution following the video amplifier. However, the size increase in the CRT and LCLV involves development work, a larger and heavier projector, and would result in more expensive LCLVs and optics.

Analysis of System Resolution – The system resolution as tabulated in Section 7 is plotted in Figure 21 for the center and edge of the projected imagery. The graph is based on component parameters which can be obtained with high confidence: video bandwidth of 30 MHz, an LCLV resolution of 40 lp/mm, and an LCLV image size of 1.6 in. The present state of the art in fiber optics does

not, at this time, allow further resolution improvement. The graph is drawn for the optics with and without the apochromatic relay lenses, and the CRT spot size is shown as a variable. Any improvement to either video bandwidth or LCLV resolution will shift the curves up on the graph by the percentage resolution increase.

Inspection of these resolution plots reveals two conditions for which the center resolution of 30% MTF at 1000 TVL can be met:

- Projection optics with apochromatic relay lenses allows the 50% spot size to be nearly 1.1 mils in the center.
- Projection optics without apochromatic relay lenses dictate a maximum 50% spot size of 0.95 mils in the center.

The choice of the higher resolution projection optics, although more expensive, is considered the better of the two approaches at this time due to the risk involved in spot size reduction. The 50% CRT spot size required to produce 30% MTF at 1000 TVL in the center is therefore 1.1 mils. If a 30% spot growth at CRT edge is assumed (1.42 mils), an edge resolution of 37% (i.e., higher than required) is produced at 750 TVL.

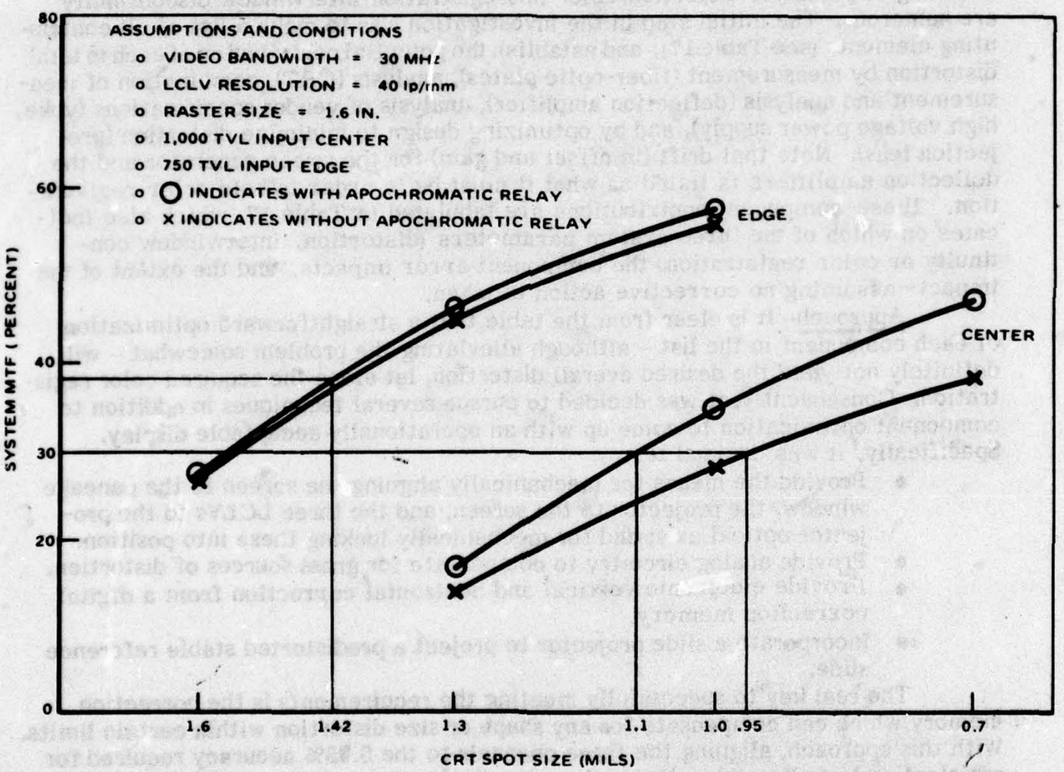


Figure 21. LCLV Color Projector Resolution versus CRT Spot Size. Improvements can be made by increasing the video bandwidth or raising the LCLV resolution resulting in an upward vertical shift of the resolution curves.

6. DEVELOPING AN APPROACH TO MINIMIZE DISTORTION AND COLOR MISREGISTRATION

The combination of stable deflection circuitry, a hybrid digital/analog position correction system, and a means of mechanically aligning projector and screen will enable attainment of a projector distortion of 0.5%, interwindow discontinuity of 1% and color registration of 0.06%.

The formal requirement of holding distortion within a single window to less than 1%, and the derived requirements of 1) holding interwindow discontinuities to less than 1%, and 2) holding color misregistration to less than 0.05% (i.e., less than half a line width) requires that special precautions be taken in the design of the deflection channel. Note that of these three, color registration is the hardest to achieve, even though the sweep generator, the projection optics, and the screen are shared by all three channels. This investigation analyzed the sources of distortion within the system, quantified them by either analysis, measurement (when possible within available funding) or estimating, and developed techniques for correcting them.

Analysis of Deflection Channel/Optical Components – The elements contributing to projector distortion/color-misregistration/interwindow discontinuity are numerous. The initial step in the investigation was to make a list of all contributing elements (see Table 17), and establish the potential contribution of each to total distortion by measurement (fiber-optic plates), analysis (CRT), combination of measurement and analysis (deflection amplifier), analysis of vendor specifications (yoke, high voltage power supply), and by optimizing design to minimize distortion (projection lens). Note that drift (in offset and gain) for the sweep generator and the deflection amplifiers is listed as what it must be in order to hold color registration. These component contributions are tabulated in Table 17, which also indicates on which of the three system parameters (distortion, interwindow continuity or color registration) the component error impacts, and the extent of the impact–assuming no corrective action is taken.

Approach– It is clear from the table that a straightforward optimization of each component in the list – although alleviating the problem somewhat – will definitely not yield the desired overall distortion, let alone the required color registration. Consequently, it was decided to pursue several techniques in addition to component optimization to come up with an operationally acceptable display. Specifically, it was decided to:

- Provide the means for mechanically aligning the screen to the pancake window, the projector to the screen, and the three LCLVs to the projector optical axis; and for mechanically locking these into position.
- Provide analog circuitry to compensate for gross sources of distortion.
- Provide electronic vertical and horizontal correction from a digital correction memory.
- Incorporate a slide projector to project a predistorted stable reference slide.

The real key to successfully meeting the requirements is the correction memory which can compensate for any shape or size distortion within certain limits. With this approach, aligning the three channels to the 0.03% accuracy required for registration looks feasible: the analog circuits compensate for gross systematic and easily correctable distortions, whereas the digital memory stores corrections (for up to a 32 x 32 points on the display area) to fine-tune the color registration.

Having aligned the system, the stability of the deflection channel must be excellent to ensure long-term stable registration of the three images. The image drift due to changes in deflection amplifier offset and gain and drifts in the

linearity/rotation circuitry (very small) cannot exceed 0.03% over the image area if total color registration is to be maintained to within 0.06% over a period of several hours without requiring realignment of the projector. (Note that the sweep generator is common to all three channels; its drift impacts interwindow continuity, but not color registration.)

Table 17. SOURCES OF DISTORTION/MISREGISTRATION AND THEIR IMPACT ON SYSTEM

Sources of Distortion/ Misregistration	Error Contribution (%)***	Has Impact On		
		Distortion	Interwindow Continuity	Color Registration
Sweep Generator				
Offset	0.05**	x	x	-
Gain	0.02**	x●	x●	-
Nonlinearity	0.01	x●	x●	-
Linearity/Rotation Ckts Drifts	0.01**	x	x	x
Deflection Amplifier				
Offset	0.02**	x	x	xx
Gain	0.01**	x	x	xx
Nonlinearity	0.02	x●	x●	x●
Yoke Nonlinearity	0.5	xx●	xx°	xx●
Yoke Nonorthogonality	1.0	xx●	xx°	xx●
CRT	0.5*	xx	xx	xx
CRT Fiber-Optic Plate	0.25	x	x	xx
HV Power Supply	0.015	-	-	x
LCLV Fiber-Optic Plate	0.25	x	x	xx
LCLV Misalignment	1.0*	xx°●	xx°●	xx
Projection Lens	0.6	xx	x	-
Screen/Projector Alignment	1.0*	xx°●	xx°	-
Screen/Pancake Window Alignment	1.0*	xx°	xx°	-

Key: x - Some impact
xx - Major impact

Primary Correction Approach:

● Analog correction circuits
o Mechanical alignment/errors except stability (two asterisk) items. All other errors are corrected with digital correction memory approach.

*Estimated value, no detailed analysis performed.
**These represent derived stability requirements.
***Uncorrected distortion contribution except for double asterisk items.

Preceding Page Blank - NOT FILMED

SECTION 6
BASELINE DESIGN DESCRIPTION

1. OVERVIEW OF THE SYSTEM

The study-recommended approach permits implementation of a high-quality, multicolor, wide-field-of-view mosaicked multiprojector system which can operate on a motion platform, has high operational availability, and can be operated at reasonable cost.

The basic reason for this study is the Air Force's need for a wide-field-of-view (FOV) simulator which can provide an effective means of training pilots of high performance fighter aircraft. The most promising technique for implementing a visual system of acceptable realism for such a simulator employs a mosaicked set of virtual image displays driven by a computer image generator (CIG), with a typical number of displays mosaicked being 7 or 8. Each display consists of a 90° FOV virtual image in-line infinity optical system (ILIOS) pancake window, a 24-inch-radius curved projection screen, and a display capable of generating a high quality (over 1000-line resolution, with uniformity and high brightness, low distortion and good edge matching) color image on the screen. The mosaicked set of projectors must be capable of operating on a motion platform to enhance simulation realism. Because of the complexity due largely to the large number of independent displays required, high system availability is of special concern: the system should be capable of reliable operation on at least a 16 hours/day schedule without requiring extraordinary maintenance support measures. Finally, operating costs (on a life-cycle-cost basis) must be kept low to meet training cost-effectiveness criteria.

In the recommended system (see Figure 22), each display uses a liquid crystal light valve (LCLV) projector coupled with a high gain screen to generate the high quality image. The projector uses a rigid optical plate as its basic structure. The projector and screen assembly are rigidly mounted to the dodecahedron frame to ensure mechanical integrity during motion platform operation. Common, redundant low/medium voltage and individual lamp power supplies for each of the projectors are housed in a central power supply cabinet. A central minicomputer, two disc units and two maintenance control panels capable of remote operation are provided to support maintenance of the system. Two projector configurations were considered. The larger one using illumination relay optics is selected as the conservative low risk baseline system. The alternate is significantly smaller in size and weight, and has 32% more light output. Though some technical risk exists, feasibility of this packaging approach appears likely.

High Quality LCLV Projector – The key to the recommended system is the use of the liquid crystal light valve. This device features high sensitivity to permit the implementation of the desired performance with low power and reliable electronics. It also permits low light absorption with good light efficiency to realize a high brightness, uniform, flicker-free image at reasonable lamp power levels. The other key concepts contributing to high light output are the use of a high gain directional, non-depolarizing screen, and the fact that the image generated is polarized, which nearly doubles the efficiency of the pancake window. Color is obtained by accurately superimposing and registering three separate channels which generate red, green and blue images, respectively, from a single light source. The desired registration between channels (for no color fringing) is achieved with the aid of a digital deflection correction memory in each channel. This technique also reduces distortion and interwindow discontinuity considerably below the specified 1 percent. Dichroics determine the spectral characteristics of the three channels, and provide growth to compatibility with a trichromatic holographic pancake window.

Motion Platform Operation – A dual approach was used to ensure structural and performance integrity under acceleration conditions encountered on a

motion platform. First, the optical elements of the projector are coplanarly mounted on a lightweight, very rigid honeycomb reinforced optical baseplate to accurately maintain tolerances during motion. Second, the projector is mounted by means of rigid, tubular struts which attach this baseplate to the dodecahedron frame structure which holds the pancake windows. The projectors are mounted perpendicularly to one facet of the pentagon to align the axes of polarization of the projector and pancake window; their orientation is optimized for accessibility. The screen is attached to a mounting plate on the dodecahedron frame, allowing independent projector alignment.

High Availability - Keys to availability are assuring good reliability, and providing a variety of maintenance features to support maintenance actions. By virtue of the low power electronics, the MTBF of one projector is estimated to be very high (over 8000 hours). With redundancy in the central power supplies, overall MTBF of mission-critical hardware (excludes minicomputer and discs) is estimated to be 1130 hours. When failures do occur, observation of various test patterns stored on disc and recalled via the minicomputer to the screen, and/or monitoring of test points in the hardware will lead to rapid isolation of a single failed card. A reference slide in each projector (initially aligned for mosaicking) is used to permit independent alignment of each projector, yet ensure system interwindow continuity.

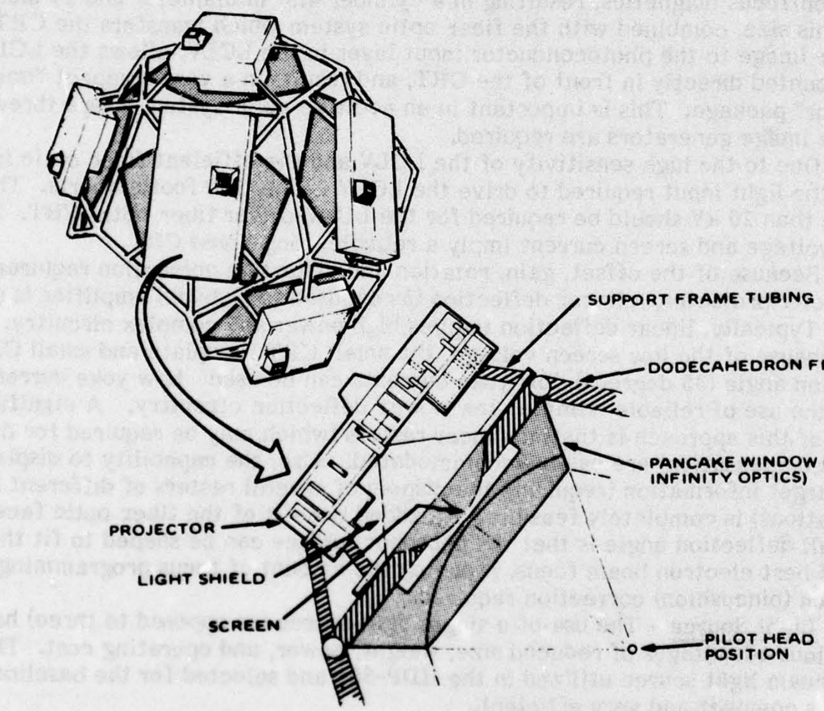


Figure 22. Overview of Multiprojector System. The projectors are mounted by support struts connected to the frame which provides rigid projector support. The screen is separately attached to a mounting plate on the dodecahedron frame.

2. FEATURES OF THE RECOMMENDED LCLV-BASED PROJECTOR DESIGN

The basic design concepts in the LCLV projector closely approach those of an idealized additive color system. Key concepts are: a small, low-light-absorption, sensitive, light valve driven by a fiber optic CRT; a single compact, efficient light source; and a collimated, polarized beam to combine and project the three color images.

The concepts underlying the design of the LCLV (low light absorption and high resolution) translate directly into tangible benefits in an additive color projector. The important LCLV design concepts are listed in Table 18, along with the hardware features they imply.

Light Valve – In simulation applications (where light output is important) the use of a light-valve approach is attractive. Assuming the light valve can take the power density in the illumination beam, light output is simply a function of the light source and condensing system, and can be made as high as the practical limitations of those elements permit. The LCLV relies on rotating the axis of polarization of the illuminating light in the liquid crystal layer to create an image. Since this is not an absorptive process, the light valve absorbs less than 4 percent of the light falling on it. Consequently, light levels of several thousand lumens are feasible.

LCLV and Driving Fiber Optic CRT – The high resolution of the LCLV (40 line pairs/mm permits the LCLV to be only 1.8 inches in diameter to provide the required resolution. The CRT is prealigned and encapsulated in a shield with the deflection/focus magnetics, resulting in a cylinder 4.5" in diameter and 14 inches long. This size, combined with the fiber optic system which transfers the CRT phosphor image to the photoconductor input layer in the LCLV, allows the LCLV to be mounted directly in front of the CRT, and results in a very compact "image generator" package. This is important in an additive color system where three separate image generators are required.

Due to the high sensitivity of the LCLV and the efficient fiber optic input optics, the light input required to drive the LCLV is only 200 footlamberts. Thus no more than 20 kV should be required for the LCLV-driver fiber optic CRT. Low screen voltage and screen current imply a reliable, long-lived CRT.

Because of the offset, gain, rotation and distortion correction requirements of the color projector, a linear deflection (as opposed to flyback) amplifier is required. Typically, linear deflection implies high power and complex circuitry. However, because of the low screen voltage, the small CRT faceplate and small CRT deflection angle (35 degrees), low yoke currents can be used. Low yoke currents permit the use of reliable, simple, low power deflection circuitry. A significant benefit of this approach is that nonlinear rasters (which may be required for distortion compensation) are easily accommodated. Also, the capability to display multi-target information (requiring the display of several rasters of different sizes and locations) is completely feasible. An added benefit of the fiber optic faceplate and small deflection angle is that the phosphor surface can be shaped to fit the plane of best electron beam focus, reducing the amount of focus programming and distortion (pincushion) correction required.

Light Source – The use of a single light source (as opposed to three) has the obvious advantages of reduced size, weight, power, and operating cost. The sealed-beam light source utilized in the HDP-800 and selected for the baseline approach is compact and very efficient.

Color-Defining Dichroics – Along with the spectral characteristics of the LCLV, selection of the dichroics and trim filters will determine the spectrum of the three projected colors. Selectability of this spectrum is important for growth to operation with a trichromatic holographic pancake window.

Illumination System – The illumination system outputs a collimated, low-diverging-angle beam to the beamsplitting, polarizing, additive color optics. Good collimation is required to obtain a high polarization ratio (hence good screen contrast) from the MacNeille prism. The collimated beam also provides a number of other benefits to an additive color projector: 1) it allows superposition of the three color images with small-diameter, compact optics, and simplifies the task of accurate superposition to minimize color misregistration; 2) the collimated system naturally lends itself to a single projection lens, eliminating color misregistration caused by differential magnification or distortion among three separate lenses; and 3) the low divergence angle of the beam entering the projection lens permits the use of telecentric optics. The f/number of the lens can be high (f/8), facilitating design of the lens of required resolution.

Polarized Light Output – A final feature of the LCLV system is that the projector output is polarized. If the depolarizing effect of the screen is minimized by using a high gain screen, and the axes of polarization of the projector and pancake optics are properly aligned, the efficiency of the pancake optics can be increased by a factor of almost 2. This is equivalent to an effective increase in projector light output by a corresponding factor.

TABLE 18. HARDWARE BENEFITS OF LCLV DESIGN CONCEPTS

Basic Design Concepts	Resulting Hardware Features
Low-absorption light valve image generator (LCLV)	– Light output function of external light source – Ease of growth to higher light output
Small, sensitive (high gain) light valve	– Compact three-channel system – Low screen voltage, easily modulated high resolution CRT (growth to higher resolution)
Fiber optic coupling between CRT and LCLV	– Low power deflection and video circuits – Linear deflection system readily adapts to non-linear raster, or subrastering, and permits the mixing of correction signals with main deflection to ensure color registration and low distortion.
Single efficient light source	– Power efficiency, lower power consumption – Small, compact illumination system feasible (see alternate approach)
Collimated illumination beam	– Simple, compact optics to combine color channels – Single projection lens to minimize color misregistration – Low f/# projection optics simplify projection lens design
Polarized light output	– Improves effective efficiency in pancake window

3. DESIGN OF THE PROJECTOR

The baseline projector is organized as a modular, easily maintained high resolution color television projection system. Major projector system groups are the electronic subsystem, the liquid crystal light valve, the optics subsystem, and the display screen.

The projector accepts inputs from the computer image generator (CIG), and projects a high brightness, high quality, 1000-line television display on a 3-foot chordal length hemispherical rear projection screen. The projector accepts both video and sync signals from the CIG. Internal test pattern generation capability is provided to permit the projector to demonstrate operation in a stand-alone mode, to simulate inputs from a CIG, and to provide off-line test/alignment capability. A block diagram of the system is shown in Figure 23.

Electronic Subsystem – The function of the electronic subsystem is to convert either external or internally generated raster sync and video signals into a bright visual image on three fiber optic faceplate CRTs to drive the three LCLVs. Control panel settings select either CIG or the display of test patterns. Controls to adjust display brightness are also included. The subsystem is divided into three identical (red, green and blue) channel electronics, and circuitry which is shared by all three (common electronics).

Each of the three identical channels consists of a deflection channel, a video channel, CRT and LCLV circuits, and a CRT. The deflection channel accepts sweep and correction signals, generates rotational and orthogonality corrections, provides for sizing and centering the image, and drives the deflection yoke of its CRT. Chopper amplifiers are utilized to ensure the stability of the deflection waveforms and minimize interchannel jitter and drift. The video channels accept external or test pattern video, compensate for LCLV characteristics, and drive the cathodes of the CRTs. The CRT is a small magnetic deflection/focus, 2-inch, high resolution fiber optic faceplate CRT that is encapsulated, along with deflection and focus magnetics, in a ruggedized shield assembly. Individual CRT and LCLV bias circuits are included in each channel.

The timing generator uses either external or internally generated sync signals to provide all timing signals for the projector. These signals are used by the sweep generator to output vertical and horizontal raster sweeps to all three channels, and by the display logic unit to output digitally stored position correction signals unique to each channel in order to ensure registration. The display logic unit also generates control-panel-selected stored test pattern video for all three channels, and can store/refresh test patterns received from the central minicomputer. Low- and medium-voltage power supplies to drive the electronics, and a xenon lamp power supply to power the light source are located off the platform in a central power supply cabinet.

Liquid Crystal Light Valve – The LCLV converts the CRT image into a birefringent pattern in a thin liquid crystal layer, which can then be projected by reflecting polarized light off an internal mirror located behind the liquid crystal. A unique LCLV is provided for each channel to maximize contrast at the fast response times required.

Optics Subsystem – One efficient, sealed beam xenon arc lamp and illumination optics within the illumination group (including a relay system which may be eliminated in the future) provides a high intensity, uniform, collimated light beam for projection of the image. In the beamsplitter polarizer group, a MacNeille prism polarizes the light, directs it to the three LCLVs through the dichroic mirrors which split the light spectrally and physically to illuminate each LCLV with one color of light, and analyzes the returned recombined light beam for projection.

The projection optics are composed of a relay lens system to reduce the effective focal length required of the projection lens, a wide angle telecentric projection lens, and prisms to fold the optical path to minimize occupied space. The optics subsystem also provides for selection of a reference background slide utilized in system alignment. The 24-inch-radius spherical rear projection screen is mounted directly to the optical plate of the projector frame holding the pancake window. Acrylic was chosen as the base material, rather than glass, in order to reduce the weight of the system. An 8-gain screen provides the required brightness at minimum light falloff with pilot head motion.

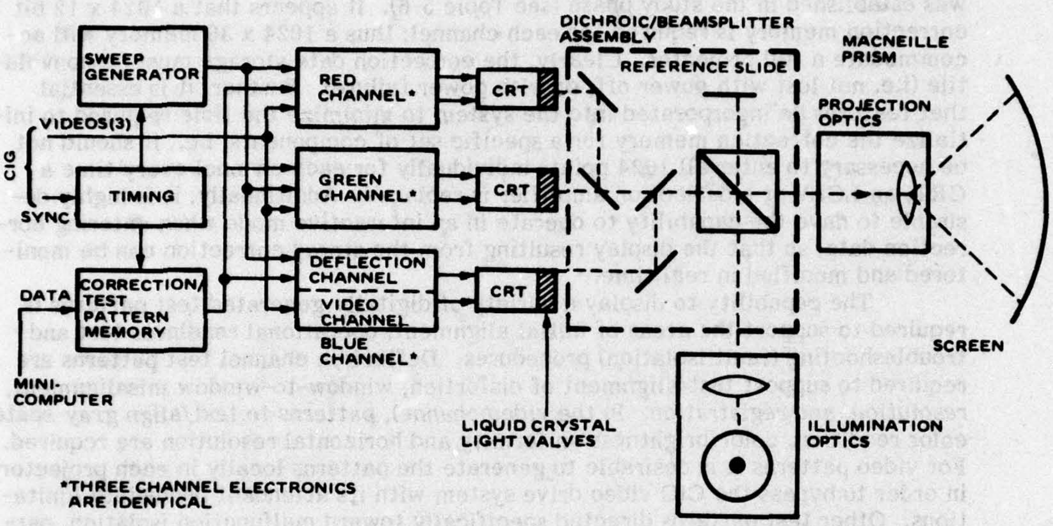


Figure 23. LCLV Color Projector Functional Organization

1. DESCRIPTION OF THE DIGITAL ELECTRONICS IN A MULTIPROJECTOR SYSTEM

Digital techniques provide the flexibility to achieve the required registration/distortion/alignment characteristics. A central minicomputer with disc storage is recommended as a low cost, versatile approach to realize an easily maintained, high availability system.

Requirements – A need to incorporate digital logic circuitry in a multiprojector system is derived from two basic requirements. First, a digital correction memory must be provided for every channel of each projector; second, there is a need to provide a variety of test patterns for system alignment, operational readiness testing, and troubleshooting.

The need for open-loop correction of the many distortions in each channel to ensure good color registration as well as to ensure window-to-window registration was established in the study phase (see Topic 5-6). It appears that a 1024 x 12 bit correction memory is required for each channel; thus a 1024 x 36 memory will accommodate a full projector. Clearly, the correction data storage must be nonvolatile (i.e. not lost with power off, or with power failure). Further, it is essential that features be incorporated into the system to minimize the time required to initialize the correction memory for a specific set of components; i.e., it should not be necessary to enter all 1024 points individually for each channel every time a CRT, an LCLV or a deflection amplifier is replaced. Additionally, it is highly desirable to have the capability to operate in an interactive mode when entering correction data, so that the display resulting from the stored correction can be monitored and modified in real time.

The capability to display a variety of digitally generated test patterns is required to support the areas of initial alignment, operational readiness test and troubleshooting (fault isolation) procedures. Deflection channel test patterns are required to support test/alignment of distortion, window-to-window misalignment, resolution, and registration. In the video channel, patterns to test/align gray scale, color rendition, color/brightness uniformity and horizontal resolution are required. For video patterns it is desirable to generate the patterns locally in each projector in order to bypass the CIG video drive system with its attendant bandwidth limitations. Other test patterns directed specifically toward malfunction isolation, particularly in the digital area, are highly desirable.

Alternatives Considered – Two basic approaches of greatly different automation and complexity/cost were considered, based on the type of correction memory used. The use of an independent programmable read-only memory (PROM) in each projector to store both correction data and test patterns, with off-line modification of the correction data, is a low cost but a very limited-speed and cumbersome approach. At the other extreme is a system based on a central minicomputer with magnetic off-line nonvolatile storage that provides interactive entry of correction data and offers a great deal of flexibility and growth. A third, intermediate approach, employing a PROM for both correction and test pattern data but providing the means to bypass it with (local or central) RAM memory for an interactive capability was also considered.

Given the complexity of a multiprojector system and the importance of achieving high operational availability, the central minicomputer and disc storage approach is an obvious choice. The cost of this approach is expected to be less than 5% of the total system, and the versatility, flexibility, growth capability, and convenience of use render this an extremely cost-effective approach.

Features of the System – The high level block diagram of Figure 24. depicts overall system organization. Correction and test pattern data are stored on disc

and are recalled and stored in the correction or test pattern memory of the selected projector by use of a common data bus. Typically, the correction RAMs are loaded automatically when the projector is powered on; test patterns are called up selectively (by projector) as specified by the maintenance operator at the remote control panel. The latter communicates with the minicomputer over the same I/O data bus which drives the projector. Several panels may be used to facilitate efficient maintenance. The panel is used to specify test patterns, to manipulate a digitally generated cursor symbol, and to enter cursor position data which are then used by the computer to generate the correction data. During alignment the correction data points entered by the operator are smoothed and interpolated by the computer program, and the results are output to the RAM correction memory immediately to provide real-time feedback to the alignment operator of the resultant display effect. Computer interpolation reduces the number of points to be entered by one to two orders of magnitude.

Given this basic architecture, a wide variety of features may be implemented, depending on availability requirements, personnel skill level and cost constraints. On-line fault monitoring, maintenance record keeping, logging operating times, automatic sequencing of maintenance actions and degraded operating modes are some of the possible features which can easily be programmed into the minicomputer-based system. Even without these extra features, however, this basic approach will yield an easily maintained, high availability multi-projector system.

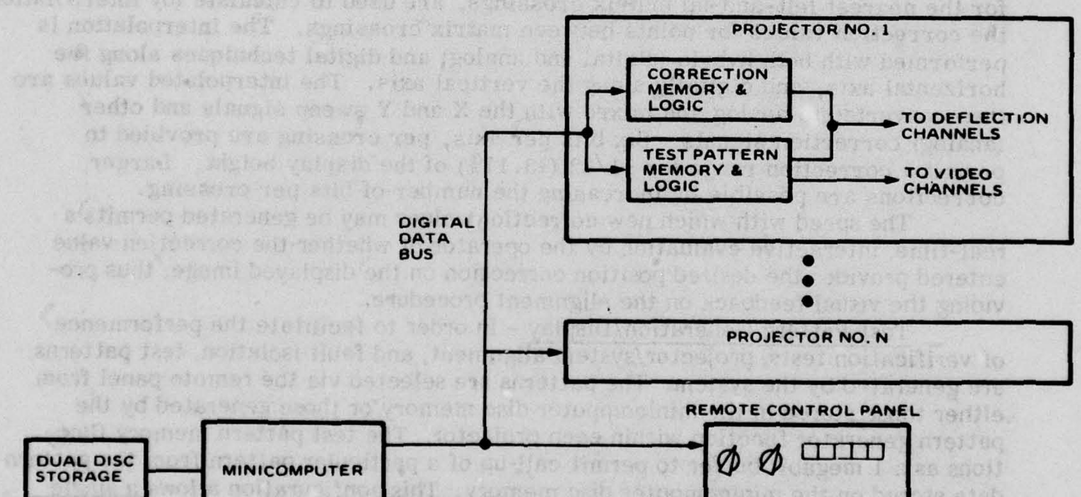


Figure 24. Block Diagram of Digital System in a Multiprojector System. The discs provide nonvolatile storage of correction memory data, and a number of test patterns to aid in the various phases of maintenance.

2. DESIGN OF THE DISPLAY LOGIC

The digital logic in the projector performs three basic functions: 1) the storage and recall of deflection correction data; 2) the storage of test patterns called up from the central minicomputer, and 3) the internal generation of test patterns.

Storage of Correction Data – The analysis of the problems in achieving the desired channel-to-channel color registration pointed to the need for a means of correcting the basic raster in each channel to 1) conform to a reference pattern projected on the screen, and 2) register with the other two channels. This correction is best implemented with a digital memory which stores the amplitude of the deflection correction required (See Figure 25). Although the raster is specified as 985 lines of 1000 elements per line, it is treated as a 1024 x 1024 raster. Since it is both impractical and unnecessary to store a correction value for all one million picture elements of a 1024 x 1024 raster, correction values will be stored for points of intersection of a 32 x 32 XY matrix (crosshatch), and correction values between these points will be calculated by linearly interpolating (along both X and Y axes) between the values stored for the nearest four points. This approach will accurately compensate for all low spatial frequency distortions (distortions in lens, CRT, yoke and fiber optics) and will only fail for small, very localized distortions such as might be caused by shear in the fiber optic plates. The procedure for entering the required corrections is discussed in Topic 7-7.

Once the X and Y correction values for all 1024 points of a 32 x 32 matrix are stored in RAM correction memory, they are read out in synchronism with the raster. Thus a new value is called up every time the raster sweeps by one of the 32 x 32 matrix crossings. These values are stored and, along with values stored for the nearest left-and-up matrix crossings, are used to calculate (by interpolation) the correction values for points between matrix crossings. The interpolation is performed with both hybrid (digital and analog) and digital techniques along the horizontal axis, and digitally along the vertical axis. The interpolated values are then converted to analog and mixed with the X and Y sweep signals and other (analog) correction signals. Six bits per axis, per crossing are provided to permit a correction range for ±1/32 (±3.17%) of the display height. Larger corrections are possible by increasing the number of bits per crossing.

The speed with which new correction values may be generated permits a real-time, interactive evaluation by the operator of whether the correction value entered provides the desired position correction on the displayed image, thus providing the visual feedback on the alignment procedure.

Test Pattern Generation/Display – In order to facilitate the performance of verification tests, projector/system alignment, and fault isolation, test patterns are generated by the system. The patterns are selected via the remote panel from either those stored in the minicomputer disc memory or those generated by the pattern generator function within each projector. The test pattern memory functions as a 1 megabit buffer to permit call-up of a particular pattern from the pattern data stored on the minicomputer disc memory. This configuration allows a single stored test pattern to be continuously refreshed, and provides a source of multiple test patterns. In addition, the pattern generator with each projector is available to provide simple, full screen, full intensity, color patterns such as checkerboard, registration, and resolution. These patterns are formed by simple counter techniques and, since they are local to the projector, provide a clean, fast rise/fall time video for focus and color alignment. The two test pattern video outputs are reshaped, mixed with the cursor (when selected), and applied to the video amplifier. This capability also represents a means of simulating a computer image generator (CIG) input.

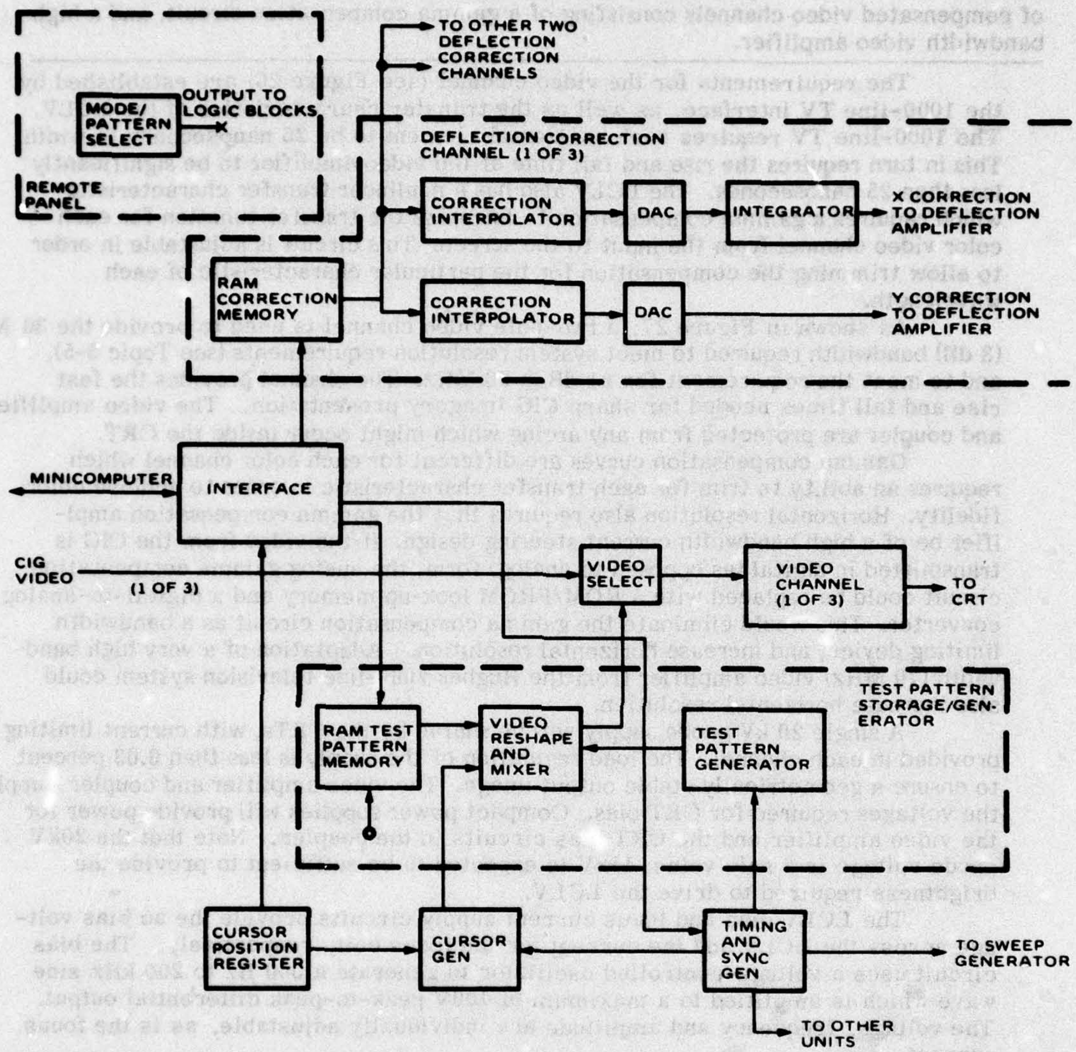


Figure 25. Display Logic Block Diagram. Local generation of test patterns and refresh storage of disc-stored test patterns provide fast rise/fall-time video signals to facilitate alignment. Easy access to a wide range of test patterns is a significant aid to performance monitoring, fault isolation, and repair.

3. REQUIREMENTS AND IMPLEMENTATION OF VIDEO CHANNEL AND OTHER CIRCUITS

Horizontal resolution requirements and LCLV transfer characteristics dictate the use of compensated video channels consisting of a gamma compensation circuit, and a high bandwidth video amplifier.

The requirements for the video channel (see Figure 26) are established by the 1000-line TV interface, as well as the transfer characteristics of the LCLV. The 1000-line TV requires each horizontal element to be 25 nanoseconds in width. This in turn requires the rise and fall time of the video amplifier to be significantly less than 25 nanoseconds. The LCLV also has a nonlinear transfer characteristic which requires a gamma compensation to linearize the transfer function for each color video channel from the input to the screen. This circuit is adjustable in order to allow trimming the compensation for the particular characteristic of each wavelength.

As shown in Figure 27, a two-pole video channel is used to provide the 30 MHz (3 dB) bandwidth required to meet system resolution requirements (see Topic 5-5), and to meet the requirement for ±1 dB @ 20 MHz. The channel provides the fast rise and fall times needed for sharp CIG imagery presentation. The video amplifier and coupler are protected from any arcing which might occur inside the CRT.

Gamma compensation curves are different for each color channel which requires an ability to trim for each transfer characteristic in order to achieve color fidelity. Horizontal resolution also requires that the gamma compensation amplifier be of a high bandwidth current steering design. If the video from the CIG is transmitted in digital (as opposed to analog) form, the analog gamma compensation circuit could be replaced with a ROM/PROM look-up memory and a digital-to-analog converter. This would eliminate the gamma compensation circuit as a bandwidth limiting device, and increase horizontal resolution. Adaptation of a very high bandwidth (70 MHz) video amplifier from the Hughes 2000-line television system could also increase horizontal resolution.

A single 20 kV anode supply will be shared by the CRTs, with current limiting provided in each channel. The load regulation of the supply is less than 0.03 percent to ensure a geometrically stable output image. The video amplifier and coupler supply the voltages required for CRT bias. Compact power supplies will provide power for the video amplifier and the CRT bias circuits in the coupler. Note that the 20kV anode voltage is a safe value; 15kV is expected to be sufficient to provide the brightness required to drive the LCLV.

The LCLV bias and focus current supply circuits provide the ac bias voltage across the LCLV and the current for the focus coil, respectively. The bias circuit uses a voltage-controlled oscillator to generate a 500 Hz to 200 kHz sine wave which is amplified to a maximum of 100V peak-to-peak differential output. The voltage, frequency and amplitude are individually adjustable, as is the focus current.

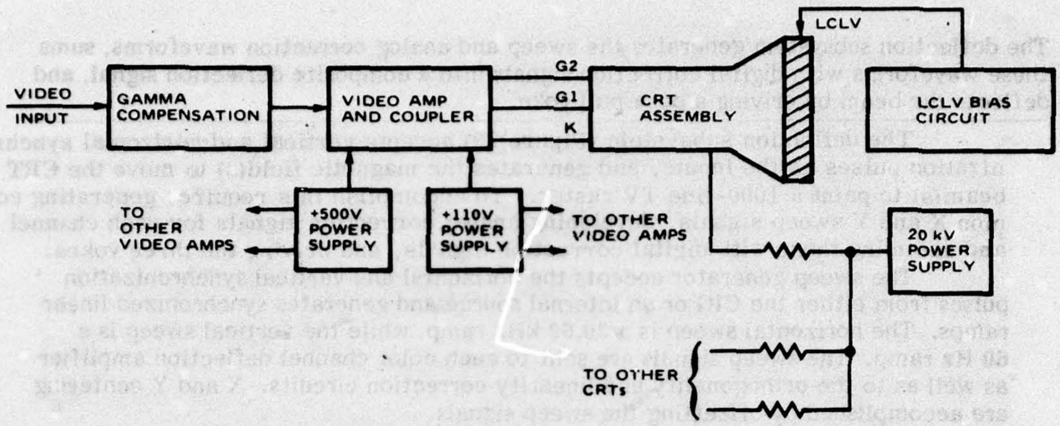


Figure 26. Typical Video Channel. Three separate video channels provide unique gamma compensation for each color channel.

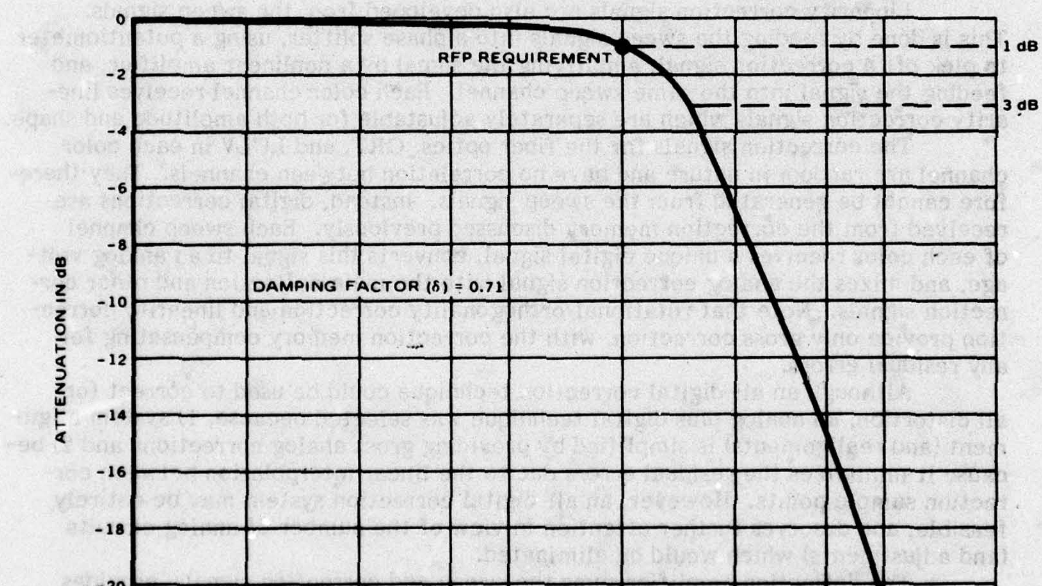


Figure 27. Video Channel Response Characteristics. A two-pole design is used to exceed the RFP required ±1 dB response up to 20 MHz, and provide a bandwidth of 30 MHz.

4. IMPLEMENTATION OF THE DEFLECTION SUBSYSTEM

The deflection subsystem generates the sweep and analog correction waveforms, sums these waveforms with digital correction signals into a composite deflection signal, and deflects the beam by driving a push-pull yoke.

The deflection subsystem (Figure 28) accepts vertical and horizontal synchronization pulses as the inputs, and generates the magnetic field(s) to move the CRT beam(s) to paint a 1000-line TV raster. To accomplish this requires generating common X and Y sweep signals, developing analog correction signals for each channel and summing these with digital correction signals, and driving the three yokes.

The sweep generator accepts the horizontal and vertical synchronization pulses from either the CIG or an internal source and generates synchronized linear ramps. The horizontal sweep is a 30.69 kHz ramp, while the vertical sweep is a 60 Hz ramp. The sweep signals are sent to each color channel deflection amplifier as well as to the orthogonality and linearity correction circuits. X and Y centering are accomplished by offsetting the sweep signals.

Rotational and orthogonality correction signals are developed on a single circuit card by feeding the differential sweep signals into a phase splitter, using a potentiometer to pick off a correction signal, and feeding it into the opposite sweep channel. Each color channel receives separately adjustable orthogonality correction signals as well as common rotation signals. Thus a portion of this card is shared by the three deflection channels.

Linearity correction signals are also developed from the sweep signals. This is done by feeding the sweep signals into a phase splitter, using a potentiometer to pick off a correction signal, amplifying the signal by a nonlinear amplifier, and feeding the signal into the same sweep channel. Each color channel receives linearity correction signals which are separately adjustable for both amplitude and shape.

The correction signals for the fiber optics, CRT, and LCLV in each color channel are random in nature and have no correlation between channels. They therefore cannot be generated from the sweep signals. Instead, digital corrections are received from the correction memory discussed previously. Each sweep channel of each color receives a unique digital signal, converts this signal to an analog voltage, and mixes the analog correction signal with the main deflection and other correction signals. Note that rotational/orthogonality correction and linearity correction provide only gross correction, with the correction memory compensating for any residual errors.

Although an all-digital correction technique could be used to correct for all distortion, an analog plus digital technique was selected because, 1) system alignment (and realignments) is simplified by providing gross analog corrections and 2) because it minimizes the residual errors due to the linear interpolation between correction sample points. However, an all-digital correction system may be entirely feasible, and deserves further attention in view of the number of analog circuits (and adjustments) which would be eliminated.

The deflection amplifier sums the sweep and correction signals, provides sensitivity adjustment for each channel, and has channel centering controls for color alignment. Should raster distortion be required, the sweep and correction signals could be summed at this point. The deflection amplifier contains both the horizontal and vertical amplifiers in one package. The amplifiers can drive a push-pull yoke capable of 35° of deflection at 20 kV anode potential. The push-pull feature requires only one positive-voltage high current supply to drive the yoke. A chopper stabilizing amplifier incorporated in a correction loop around the deflection amplifier reduces the offset drift to less than 0.02 percent (equivalent to ± 1/2 line width) between channels. Gain stabilization circuitry is incorporated to hold amplifier gain accurate to 0.01%.

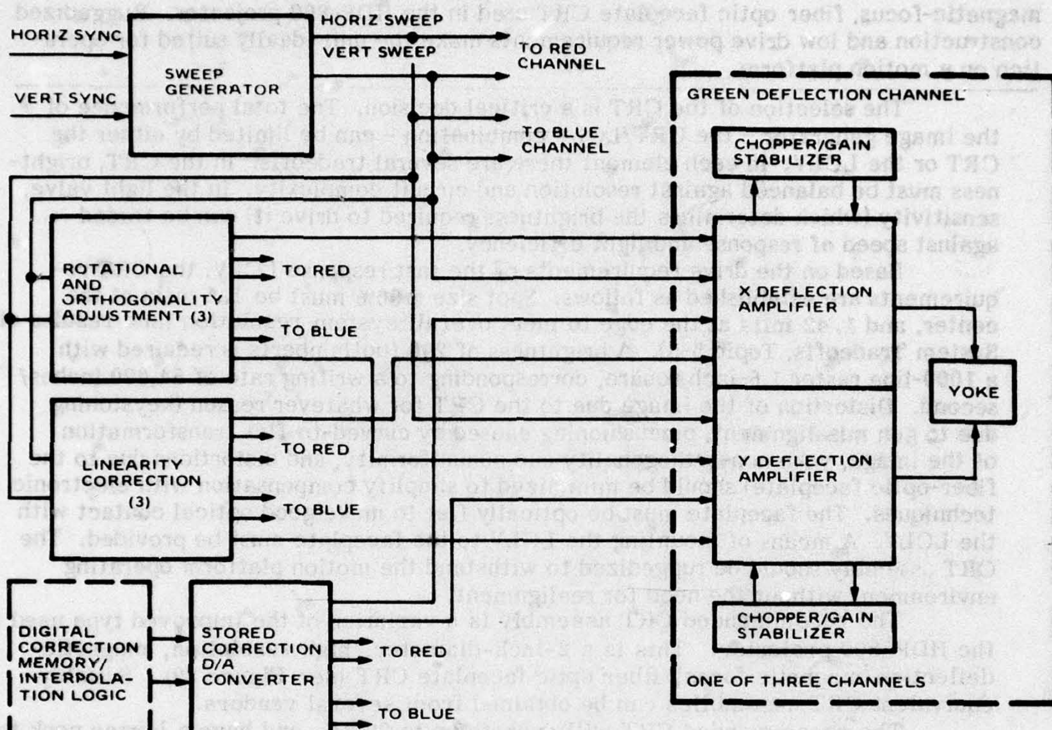


Figure 28. Projector Deflection System. The sweep and correction signals are summed in order to drive the deflection amplifiers to generate three coincident rasters.

5. DESCRIPTION OF THE HIGH-RESOLUTION FIBER OPTIC CRT

The CRT is a variation of a 2-inch-diameter, high resolution, magnetic-deflection/magnetic-focus, fiber optic faceplate CRT used in the HDP-800 projector. Ruggedized construction and low drive power requirements make the unit ideally suited for operation on a motion platform.

The selection of the CRT is a critical decision. The total performance of the image generator – the CRT/LCLV combination – can be limited by either the CRT or the LCLV. In each element there are several tradeoffs. In the CRT, brightness must be balanced against resolution and circuit complexity. In the light valve, sensitivity (which determines the brightness required to drive it) can be traded against speed of response and light efficiency.

Based on the drive requirements of the fast response LCLV, the CRT requirements are established as follows. Spot size @50% must be 1.1 mils at the center, and 1.42 mils at the edge to meet overall system resolution (see results of System Tradeoffs, Topic 5-5). A brightness of 200 footlamberts is required with a 1000-line raster 1.6-inch square, corresponding to a writing rate of 64,000 inches/second. Distortion of the image due to the CRT for whatever reason (keystoning due to gun misalignment, pincushioning caused by curved-to-flat transformation of the image, yoke non-orthogonality and nonuniformity, and distortions due to the fiber-optic faceplate) should be minimized to simplify compensation with electronic techniques. The faceplate must be optically flat to make good optical contact with the LCLV. A means of mounting the LCLV to the faceplate must be provided. The CRT assembly should be ruggedized to withstand the motion platform operating environment without the need for realignment.

The recommended CRT assembly is a variation of the improved type used in the HDP-800 projector. This is a 2-inch-diameter, high resolution, magnetic-deflection/magnetic focus, fiber optic faceplate CRT (see Figure 29). Suitably equivalent CRT assemblies can be obtained from several vendors.

The recommended CRT will operate up to 20 kV, and have a larger neck than that currently used. The CRT assembly and a prealigned yoke and focus coil are potted inside of the magnetic shield assembly, providing a very compact, rugged assembly. The CRT uses a P1 phosphor whose persistence and spectral response match that of the LCLV photoconductor. With a 15 kV anode voltage, the CRT is expected to be capable of drawing a raster line in excess of 200 fL peak brightness while maintaining a spot diameter of less than 1.1 mils at the 50 percent point at a 30-Hz refresh rate and a writing rate of 64,000 inches per second.

Pincushioning and defocusing problems can be solved in a number of ways. In general these effects are minimized by using the small deflection angle (35°). The pincushioning is eliminated by using a fiber optic faceplate which has an inside radius equal to the radius of deflection and by summing a correction signal into the deflection channel. The defocusing problem (which is caused by focusing action of the deflection yoke magnetic field) will require either dynamic focusing correction, or a fiber optic faceplate ground such that the inside surface corresponds to the crossover image position in the static focus condition. This surface does not correspond to the geometry required to match the radius of deflection, presenting a tradeoff which will be made during final design. The outer surface of this fiber optic faceplate is held flat to 2 μm to avoid loss of resolution at the interface to the fiber optics of the LCLV.

The larger CRT neck size and a high quality, large radius focus coil will minimize aberrations due to beam bundle size and achieve the required spot size. The deflection yoke will be carefully designed to minimize deflection astigmatism.

TABLE 19. RECOMMENDED CRT FEATURES

Feature	Benefit
Large (1-7/16) neck with large aperture magnetics	Reduces focus coil aberration
	Reduces deflection defocusing
	Permits higher anode voltage (minimizes arc-over problem)
Curvature of fiber optic face-plate optimized for focus	Minimizes/eliminates need for dynamic focus programming
Increased screen voltage	Increased brightness/ resolution

Figure 29. H-1345 AP1 CRT Assembly Used in HDP-800. Assembly includes shield, yoke, focus coil and CRT, potted to yield a ruggedized package. Recommended CRT will use larger diameter electron gun and magnetics.

1. OVERVIEW OF THE OPTICS SUBSYSTEM

The major features of Hughes' optics subsystem are an efficient light collection system to collimate and homogenize the light, a highly efficient polarizing system, relay optics to allow the insertion of dichroic beamsplitting plates, and a 13-element, telecentric, 90-degree projection lens.

The function of the optics subsystem is to provide illumination for the LCLVs and to collect and image the polarized light on the projection screen. The specification requirement for 480 fL brightness for additive white at the input to the Farrand pancake window was used to develop the optical system and optics subsystem. Figure 30 diagrams the overall optics subsystem. The optics subsystem consists of the illumination group, dichroic/LCLV group and projection optics group. Efficiencies of the individual groups are listed on the figure and can be multiplied to yield an overall system efficiency of 0.64 percent. The 1.6 kW xenon lamp module generates 39,000 lumens when new. This output decreases approximately 10 percent in the first 100 hours of operation to 35,400 lumens. Using this number for calculation and a 22 percent efficiency figure for the illumination group produces 7,788 lumens to the light valve/dichroic group. The overall efficiency of this group is 5 percent. This efficiency passes 389 lumens to the projection optics group. Since the efficiency of the projection optics group with H.E.A coatings is 59 percent, a total of 226 lumens are delivered to the projection screen. Projected on the 6.75 ft^2 8-gain screen, this will yield the required brightness to the pilot.

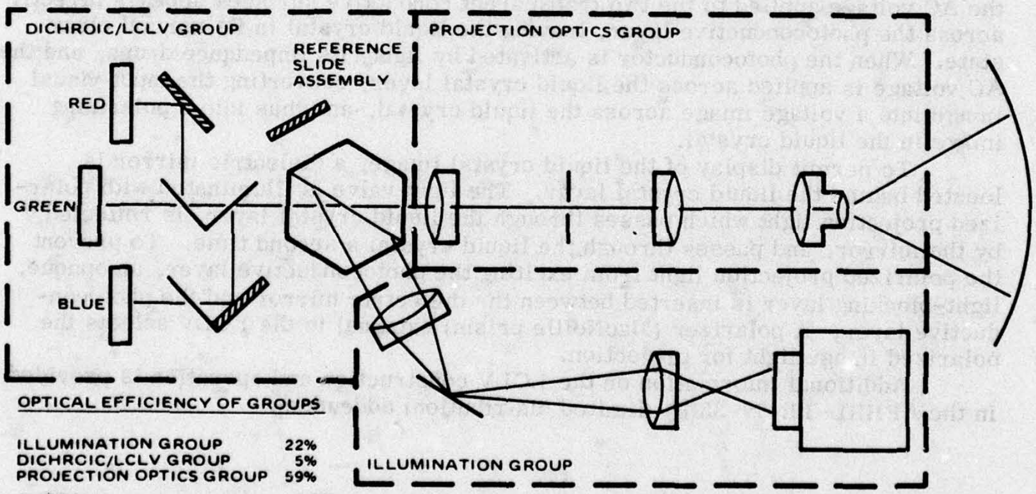
The illumination group consists of a prefocused, potted, 1.6 kW xenon lamp module, a collection system based on solar simulator design, and a relay system. The lamp intensity can be adjusted over a wide range to permit the matching of edge intensities between adjacent channels. A new longer focal length reflector is presently being designed for the lamp which may allow removal of the relay optics in this group. This would increase the efficiency of this group from 22 percent to 29 percent.

The dichroic/LCLV group contains the polarizing prism, dichroic beamsplitters and compensation plates, and the liquid crystal light valve (LCLV). The polarizing prism is made of fused silica to withstand the intense light energy passing through it. It splits the incident light beam from the illumination group into two beams of light. The beam polarized into the parallel component, P, passes straight through the prism while the other beam which is polarized perpendicularly, S, is reflected into the dichroic mirrors. There the S beam is further split into three beams – one centered at 465 nm, one at 540 nm and one at 612 nm. The compensating plates in each channel adjust the total thickness of glass each beam must pass through. This thickness must be the same in all channels to allow the correction plates in the projection group to remove the astigmatism introduced by this glass. As the light is reflected from each individual light valve, some or all of S is rotated into P, depending on the degree of light valve modulation. The reflected S and P light from the three LCLVs is recombined by the dichroic mirrors and is analyzed by the polarizing prism. The S polarization is reflected to the illumination group and the P polarization passes through the prism to the projection lens group where it is imaged on the projection screen.

The challenging projection optics design study was subcontracted to Kollmorgen Corporation's Electro-Optical Division. The primary component of the projection group is a complex, 13-element, telecentric projection lens which was designed to take the flat image at the LCLV and project it onto a spherical projection screen, with all principal rays normal to that surface. This projection lens was specifically designed for this application of the liquid crystal light valve technology.

To solve the dilemma of the long back focal length to effective focal length ratio, a telecentric optical relay system is required to interface this unique projection lens with the dichroic/LCLV group. The relay optics "stretch" the back focal length of the projection lens so that there is room to insert the dichroic beam splitter mirrors. Although the required relay optics lengthen the overall optical path, the use of a folding Porro prism allows the lens system to be folded into a package of reasonable dimensions. The projection optics are supplied mounted on an optical plate, prealigned, and are installed as an integral assembly.

The initial P beam passing through the polarizing prism can be used to project a reference alignment slide on the screen. The reference slide assembly consists of a quarter-wave plate, the slide, and a first surface mirror. The incident P beam is changed to circular polarized light by the quarter-wave plate, and is then density modulated by the slide. When the light is reflected from the mirror, it undergoes a phase reversal. When this light passes back through the quarter-wave plate, it emerges as S polarization. This light is now reflected by the polarizing prism and is imaged on the screen by the optical system. The depolarizing action of the screen will generate a P-polarized image of sufficient intensity to provide a bright background reference pattern. Mechanical means of adjusting the X/Y/Z position of the slide and its orientation will be provided. The crosshatch test pattern projected by this slide on the screen is used to align adjacent projections to each other to minimize interwindow discontinuities.



OPTICAL EFFICIENCY OF GROUPS

ILLUMINATION GROUP	22%
DICHROIC/LCLV GROUP	5%
PROJECTION OPTICS GROUP	59%
OVERALL	0.64%

Figure 30. Optics Subsystem. Careful optimization of the illumination optics, the dichroics and projection optics coupled with a high gain screen of low depolarization provide the desired brightness to the pilot through the pancake window.

2. DESCRIPTION AND OPERATION OF THE LIQUID CRYSTAL LIGHT VALVE

The Hughes-developed liquid crystal light valve is a unique light amplification device which together with the other optical and electronic elements provides a high brightness, high resolution projector system.

The hybrid field effect type photoactivated liquid crystal light valve has been developed to its present state by the Hughes Research Laboratories in a series of IR&D and funded efforts over the last several years. Research and development is continuing on new devices using similar technology, on improvements to the existing LCLV, and on applications of the devices. Hughes Research Laboratories developed the twisted nematic liquid crystal used in the LCLV.

The construction of a typical birefringent LCLV involves multiple layers of materials built up by thin film deposition techniques. These layers may be illustrated by considering a cross section of a small portion of the LCLV as shown in Figure 31. Except for the thick glass supporting structure, the thickness of the various layers is very small compared to the other dimensions of the LCLV. The LCLV is insensitive to shock and vibration because of the extreme thinness of the liquid crystal layer and because of the strength of the 0.5 inch-thick glass support layer.

The LCLV field effect mechanism is illustrated in Figure 32. The principle of operation of the LCLV cell is best described by considering the cell simply as a CdS photoconductive layer and a liquid crystal layer of small thickness sandwiched between two transparent conductive surfaces. With the photoconductor unexposed, the AC voltage applied to the two transparent conductive surfaces appears directly across the photoconductive layer, leaving the liquid crystal in its normal clear state. When the photoconductor is activated by light, its impedance drops, and the AC voltage is applied across the liquid crystal layer, converting the input visual image into a voltage image across the liquid crystal, and thus into a polarizing image in the liquid crystal.

To permit display of the liquid crystal image, a dielectric mirror is located behind the liquid crystal layer. The light valve is illuminated with polarized projection light which passes through the liquid crystal layer, is reflected by the mirror, and passes through the liquid crystal a second time. To prevent the polarized projection light from exciting the photoconductive layer, an opaque, light-blocking layer is inserted between the dielectric mirror and the photoconductive layer. A polarizer (MacNeille prism) external to the LCLV selects the polarized image light for projection.

Additional information on the LCLV construction and operation is provided in the AFHRL-TR-77-33(II) (limited distribution) addendum.

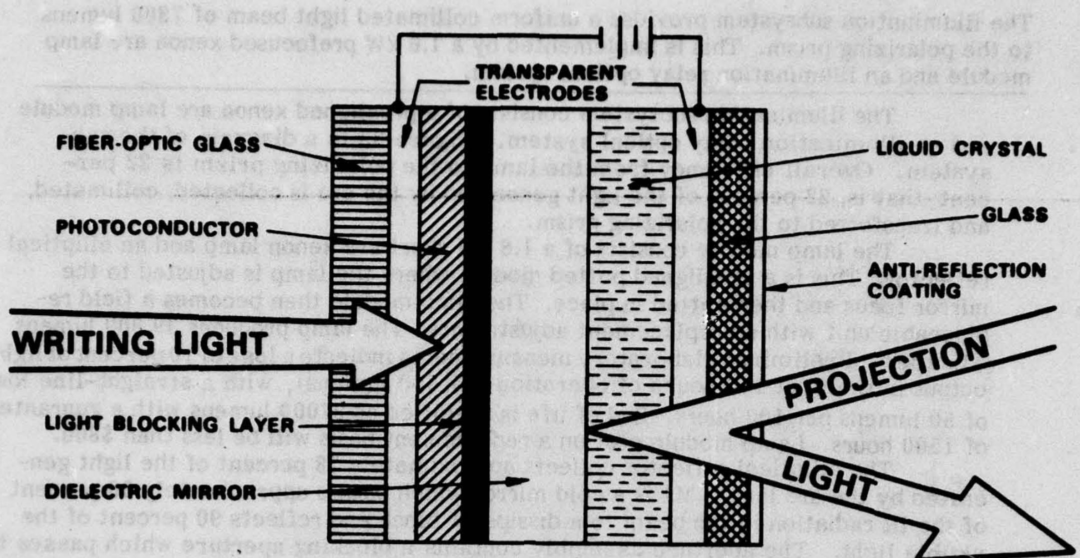


Figure 31. LCLV Cell Construction. A cross section of a small portion of a LCLV cell show the multiple layers of materials built up by thin film deposition techniques.

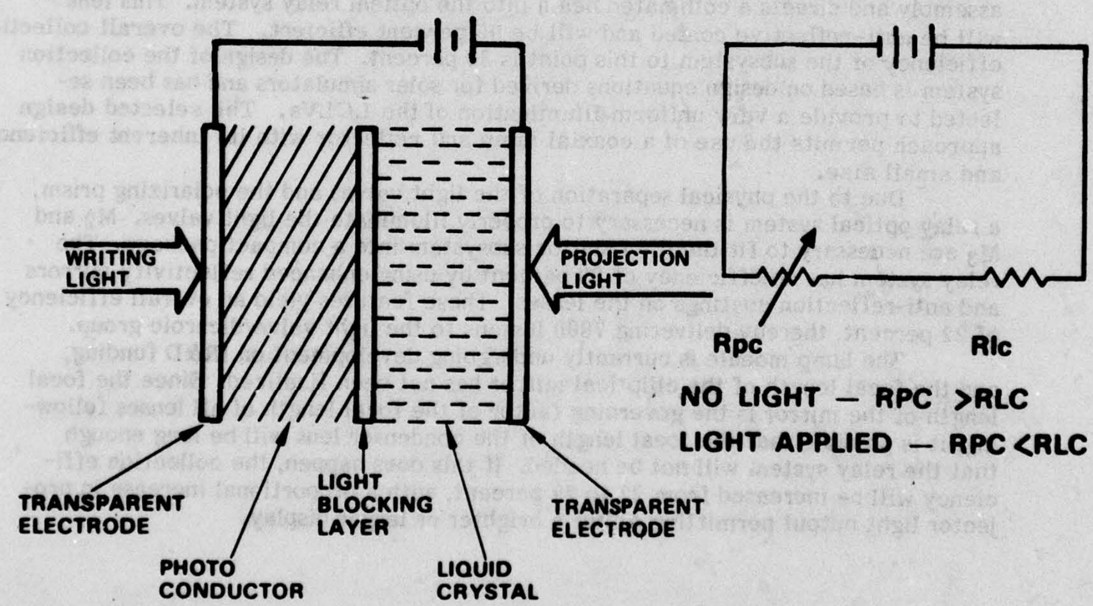


Figure 32. LCLV Field Effect Mechanism. The incident writing light varies the electric field which controls the degree of tilt and the polarizing effect on the projection light.

3. CHARACTERISTCS OF THE ILLUMINATION SUBSYSTEM

The illumination subsystem provides a uniform collimated light beam of 7800 lumens to the polarizing prism. This is implemented by a 1.6 kW prefocused xenon arc lamp module and an illumination relay optical system.

The illumination subsystem consists of a prealigned xenon arc lamp module and an illumination relay optical system. Figure 33 is a diagram of the subsystem. Overall efficiency from the lamp to the polarizing prism is 22 percent; that is, 22 percent of the light generated by the arc is collected, collimated, and transferred to the polarizing prism.

The lamp module consists of a 1.6 kW short arc xenon lamp and an elliptical reflector. This is a prealigned potted module where the lamp is adjusted to the mirror focus and then potted in place. The lamp module then becomes a field replaceable unit with no replacement adjustments. The lamp produces 39,000 lumens when new. Preliminary laboratory measurements indicate a loss of 10 percent of light output in the first 100 hours of operation (35,400 lumens), with a straight-line loss of 50 lumens per 100 hours. End of life is specified as 27000 lumens with a guarantee of 1500 hours. Lamp module cost on a replacement basis will be less than $800.

The elliptical reflector collects approximately 78 percent of the light generated by the arc lamp. M1 is a cold mirror which passes approximately 90 percent of the IR radiation in the beam to a dissipator block and reflects 90 percent of the visible light. The aperture assembly contains a blocking aperture which passes the light rays only within an f/8.0 cone and a field lens to direct the light rays into the condenser lens. The assembly also contains a hot mirror to reflect the remaining IR energy back to the light source. The overall efficiency of the aperture assembly is 45 percent. The condenser lens collects the light rays passed by the aperture assembly and directs a collimated beam into the optical relay system. This lens will be anti-reflective coated and will be 95 percent efficient. The overall collection efficiency of the subsystem to this point is 30 percent. The design of the collection system is based on design equations derived for solar simulators and has been selected to provide a very uniform illumination of the LCLVs. The selected design approach permits the use of a coaxial lamp and reflector with its inherent efficiency and small size.

Due to the physical separation of the light valves and the polarizing prism, a relay optical system is necessary to properly illuminate the light valves. M_2 and M_3 are necessary to fit the illumination subsystem into a compact package. The relay system has an efficiency of 80 percent by using enhanced reflectivity mirrors and anti-reflection coatings on the lenses. These features yield an overall efficiency of 22 percent, thereby delivering 7800 lumens to the light valve/dichroic group.

The lamp module is currently undergoing development on IR&D funding, and the focal length of the elliptical mirror has not been finalized. Since the focal length of the mirror is the governing factor of the focal length of all lenses following, it is possible that the focal length of the condenser lens will be long enough that the relay system will not be needed. If this does happen, the collection efficiency will be increased from 22 to 29 percent, with a proportional increase in projector light output permitting either a brighter or larger display.

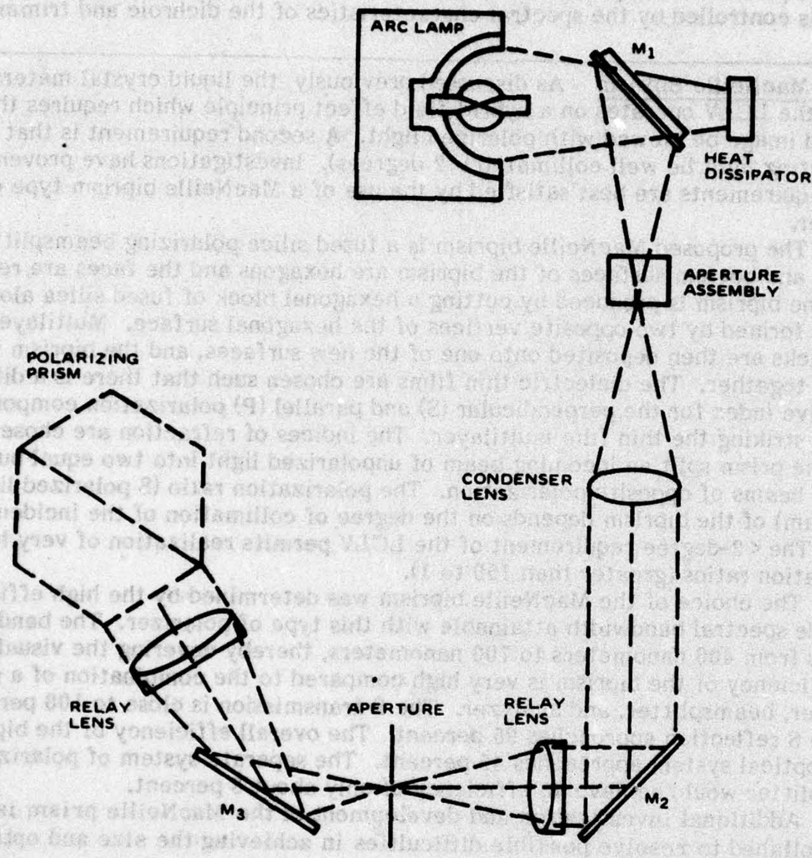


Figure 33. Illumination Subsystem. The highly efficient collection system uses techniques developed for solar simulators to provide 7800 lumens in a collimated, uniform brightness light beam to the polarizing prism.

4. DESCRIPTION OF THE POLARIZING BEAMSPLITTER AND DICHROICS

The optical subsystem achieves high efficiency through the use of a MacNeille biprism acting as the polarizer/analyzer and beamsplitter. The purity of the color spectrum obtainable is controlled by the spectral characteristics of the dichroic and trimming filters.

<u>MacNeille Biprism</u> – As discussed previously, the liquid crystal material used in the LCLV operates on a hybrid-field effect principle which requires that the field image be viewed with polarized light. A second requirement is that the illuminating light be well collimated (< 2 degrees). Investigations have proven that these requirements are best satisfied by the use of a MacNeille biprism type of polarizer.

The proposed MacNeille biprism is a fused silica polarizing beamsplitter. The top and bottom surfaces of the biprism are hexagons and the faces are rectangles. The biprism is produced by cutting a hexagonal block of fused silica along the line formed by two opposite vertices of the hexagonal surface. Multilayer thin film stacks are then deposited onto one of the new surfaces, and the biprism is cemented together. The dielectric thin films are chosen such that there is a different refractive index for the perpendicular (S) and parallel (P) polarization components of light striking the thin film multilayer. The indices of refraction are chosen to make the prism split an incoming beam of unpolarized light into two equal but diverging beams of opposite polarization. The polarization ratio (S polarized light in P beam) of the biprism depends on the degree of collimation of the incident light beam. The < 2-degree requirement of the LCLV permits realization of very high polarization ratios (greater than 150 to 1).

The choice of the MacNeille biprism was determined by the high efficiency and wide spectral bandwidth attainable with this type of polarizer. The bandwidth extends from 400 nanometers to 700 nanometers, thereby covering the visual band. The efficiency of the biprism is very high compared to the combination of a separate polarizer, beamsplitter, and analyzer. The P transmission is close to 100 percent and the S reflection approaches 95 percent. The overall efficiency of the biprism in the optical system approaches 45 percent. The separate system of polarizer and beamsplitter would achieve an efficiency of only about 8 percent.

Additional investigation and development of the MacNeille prism is being accomplished to resolve possible difficulties in achieving the size and optical characteristics required.

<u>Dichroics</u> - The S-polarized light reflected by the biprism is directed to the first dichroic filter, which reflects the blue light to the LCLV in the blue channel and transmits red and green light. The red portion of the transmitted red and green light is reflected to the LCLV in the red channel and the green light is transmitted to the LCLV in the green channel by the cyan dichroic.

In the areas of the liquid crystal material where there is no field image, the S polarized light is rotated through 45° by the liquid crystal, but upon reflection from the dielectric mirror as light passes through the liquid crystal a second time the polarization is rotated back to the direction of the incident light and is then returned to the biprism. Here the thin film polarizing layer reflects this light into the illumination system. Hence no light passes through the prism to the lens and the screen is dark. This same effect takes place in all three channels. However, in those areas of the liquid crystals where a field image exists, the liquid crystal molecules which are usually oriented such that their long axes are parallel to the electrode surfaces, begin to tilt to a perpendicular position. The amount of tilt is proportional to the field strength or the intensity of the image

It is in this orientation, between parallel and perpendicular, that the optical birefringence of the molecules affects the polarization of light such that the light emerging from the LCLV after reflection from the dielectric mirror is partially of the other axis of polarization (P state of polarization) in those localized areas where the image exists. When this light reaches the biprism, the P polarized part of the light is transmitted by the biprism and the projection lens images the light on the screen. Since the projected image is polarized - except for some (5 percent) depolarization by the screen - approximately 95 percent of the light incident upon the first polarizer in the pancake window is passed to form an image to the pilot. In contrast, more than 50 percent of the projected image's intensity would be lost at the first polarizer if a conventional system with an unpolarized projected image were used.

As shown in Figure 34, dichroic filters are used to separate the polarized illumination beam into three primary colors, which then illuminate the light valves (see Topic 4-6 for explanation of dichroics operation). Trim filters will be used in the green and red channels to balance them against the blue channel for a good illuminant C white when all channels are added. However, the baseline projector will not use a trim filter in the blue channel since the trim filters are relatively inefficient with a peak transmission of approximately 75 percent and since a light valve tuned for the blue region of the visible spectrum tends to be less efficient than light values tuned for the green and red regions.

The dichroics, trimming filters, and second surface mirrors will be mounted on a single plate and will be factory prealigned to facilitate installation onto the projector baseplate.

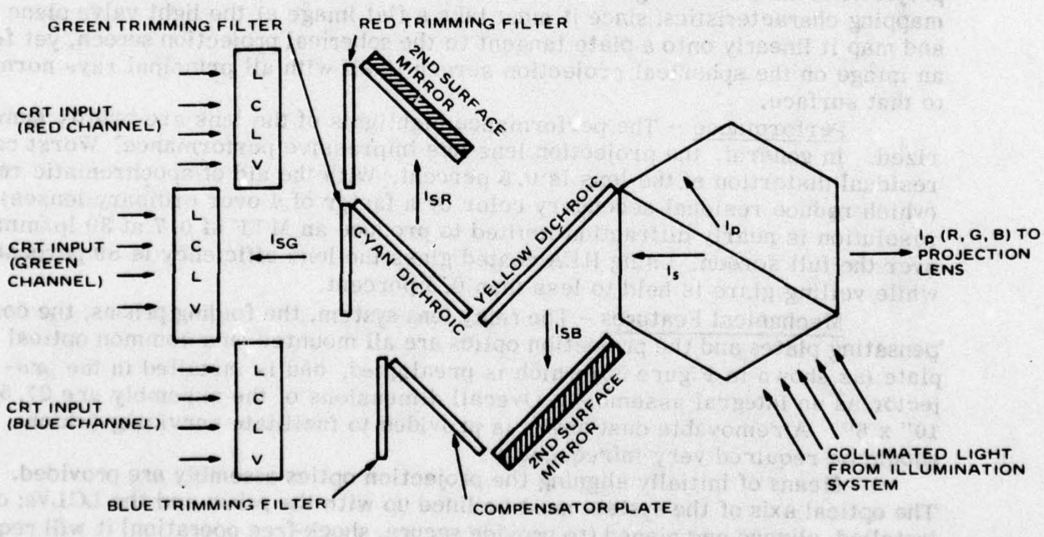


Figure 34. Beamsplitter/Dichroic Filter Arrangement. Each LCLV is illuminated in a different S polarized primary color by dichroic mirrors which separate the illumination light into the three primary colors.

5. DESIGN OF THE PROJECTION OPTICS GROUP

Projecting the LCLV image on a 24-inch-radius curved screen with unique mapping characteristics at high resolution and low light falloff is a significant technical challenge. A 9-month design study by Kollmorgen defined a projection optics group that will deliver the desired performance.

The proposed projection optics system is shown in Figure 35. It consists of a telecentric relay lens system, a folding Porro prism, compensating plates, a right-angle prism, and a complex projection lens.

Relay Lens System – The projection lens is basically an inverted telephoto type due to the requirement for a long back focal length to accommodate the polarizing prism, dichroic plates, and light valves. Because of the long back focal length to effective focal length ratio of this scheme, a 1:1 relay system is used to transfer the LCLV images to the focal plane of the projection lens. The need for high resolution and high efficiency dictate the use of an apochromatic relay and HEA coating on all lens surfaces, respectively.

Folding Prisms – Because the relay system is quite long – approximately four times the effective focal length of 400 mm, two folding prisms are used to reduce the overall space requirements. The first, a Porro prism, provides a 180-degree bend without image reversal; while the second, a 90-degree prism, provides the final bend to the projection lens which is perpendicular to the rest of the optical plane. The use of the Porro prism folds over the required path to reduce its length by half.

Compensating Plates – Compensating plates are placed between the relay optics and the right-angle prism to eliminate the astigmatism introduced by the two dichroic beamsplitting plates. Some coma and lateral color are introduced by the plates, but their magnitude is so small that performance is essentially unaffected.

Projection Lens – The projection lens is a complex, 13-element, telecentric projection lens with a magnification of 19.8 to 1. This projection lens has unique mapping characteristics, since it must take a flat image at the light valve plane and map it linearly onto a plate tangent to the spherical projection screen, yet form an image on the spherical projection screen itself with all principal rays normal to that surface.

Performance – The performance highlights of the lens are briefly summarized. In general, the projection lens has impressive performance. Worst case residual distortion of the lens is 0.5 percent. With the aid of apochromatic relays (which reduce residual secondary color by a factor of 4 over ordinary lenses), resolution is nearly diffraction limited to produce an MTF of 0.7 at 30 lp/mm over the full screen. Using HEA coated glass the lens efficiency is 59 percent while veiling glare is held to less than 0.5 percent.

Mechanical Features – The relay lens system, the folding prisms, the compensating plates and the projection optics are all mounted on a common optical plate (as shown in Figure 35) which is prealigned, and is installed in the projector as an integral assembly. Overall dimensions of the assembly are 27.5" x 10" x 6". A removable dust cover is provided to facilitate servicing (which should be required very infrequently).

Means of initially aligning the projection optics assembly are provided. The optical axis of the system must be lined up with the prism and the LCLVs; once installed, aligned and pinned (to provide secure, shock-free operation) it will require no further servicing unless an optical element is replaced.

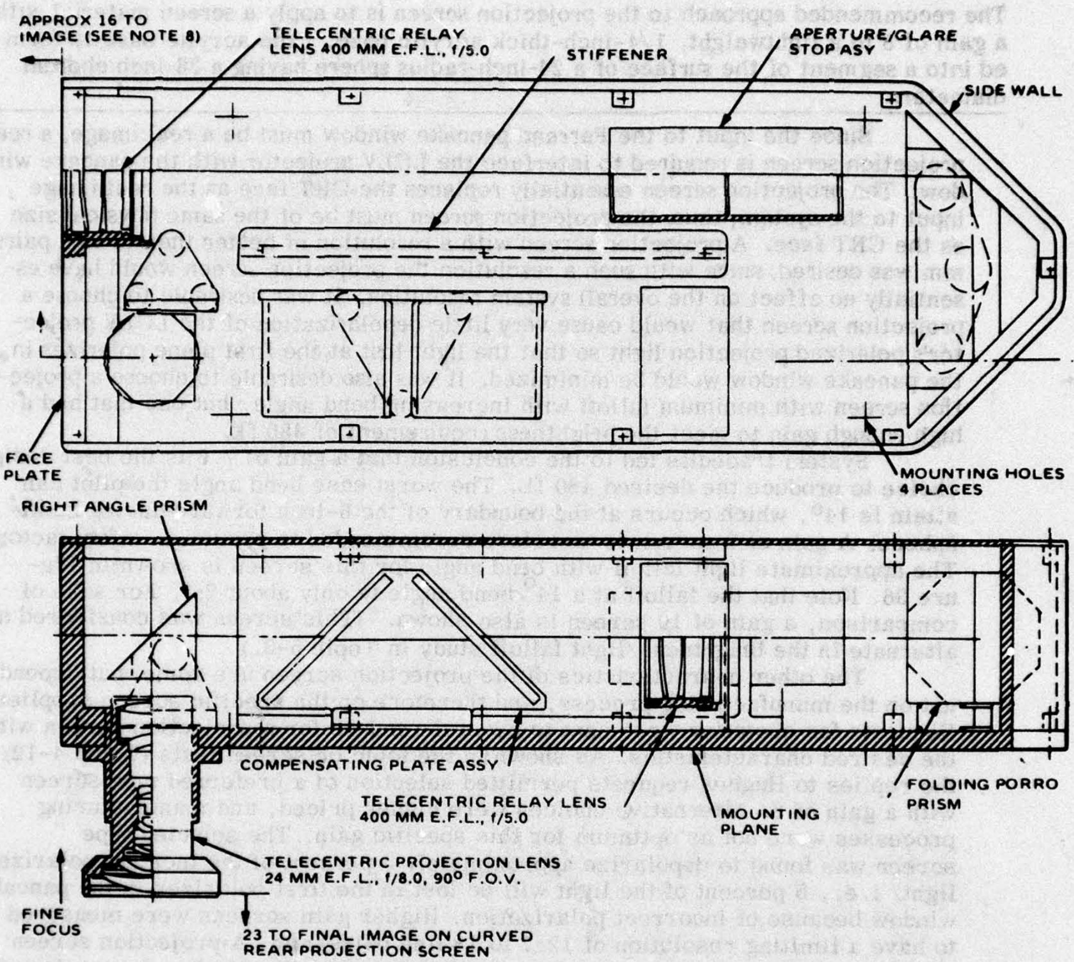


Figure 35. Top View and Side View of Projection Optics. A Porro prism folds the optical path to facilitate packaging of the projector. Tipped plates are inserted to compensatc for tipped dichroic surfaces in the rear space.

6. DESIGN OF CURVED PROJECTION SCREEN

The recommended approach to the projection screen is to apply a screen material with a gain of 8 to a lightweight, 1/4-inch-thick acrylic base. The acrylic base is formed into a segment of the surface of a 24-inch-radius sphere having a 36-inch chordal diameter.

Since the input to the Farrand pancake window must be a real image, a rear projection screen is required to interface the LCLV projector with the pancake window. The projection screen essentially replaces the CRT face as the real image input to the system; thus, the projection screen must be of the same physical size as the CRT face. A projection screen with a resolution of better than 10 line pairs/mm was desired, since with such a resolution the projection screen would have essentially no effect on the overall system resolution. It was desirable to choose a projection screen that would cause very little depolarization of the LCLV projector's polarized projection light so that the light lost at the first plane polarizer in the pancake window would be minimized. It was also desirable to choose a projection screen with minimum falloff with increasing bend angle, but one that had a high enough gain to meet the brightness requirement of 480 fL.

System tradeoffs led to the conclusion that a gain of 7.6 is the best design choice to produce the desired 480 fL. The worst case bend angle the pilot can attain is 14°, which occurs at the boundary of the 6-inch forward-facing hemisphere. A gain of 8 screen is therefore recommended to provide a safety factor. The approximate light falloff with bend angle for this screen is shown in Figure 36. Note that the falloff at a 14° bend angle is only about 2:1. For sake of comparison, a gain of 10 screen is also shown. (This screen was considered as an alternate in the brightness/light falloff study in Topic 5-3.)

The other characteristics of the projection screen are somewhat dependent on the manufacturing process, and therefore on the specific screen supplier. Requests for quotation were sent to several vendors for a projection screen with the desired characteristics. As shown in the topic on screen tests (Topic 4-12), the replies to Hughes requests permitted selection of a preferred type screen with a gain of 8. Alternative choices were higher priced, and manufacturing processes were not as optimum for this specific gain. The selected type screen was found to depolarize approximately 5 percent of the incident polarized light/ i.e., 5 percent of the light will be lost in the first polarizer in the pancake window because of incorrect polarization. Higher gain screens were measured to have a limiting resolution of 12.7 to 18 line pairs/mm. A projection screen with this much resolution can easily provide the on-axis and off-axis resolution requirements. Based on screen investigation (Topic 4-12) the contrast ratio is estimated to be 250:1.

The selected type projection screen has an optical coating which is a translucent material consisting of fine-grain diffusing particles bonded within a film. The optical coating is 9 mils thick and is produced so as to maintain uniformity of thickness (and therefore optical density) to within ±0.5 percent throughout the entire screen area. The optical coating is bonded to a clear, 1/4-inch acrylic substrate. The selected type screen is washable, scratch resistant, non-yellowing, nonfading, and fire-and-fungus resistant.

The hemispherical 24-inch-radius screen is made of 1/4-inch acrylic substrate (to which the optical coating is applied). A flange is provided to mount the screens, with means (such as shimming) provided for alignment positioning (in X, Y, Z and tilt) and for locking the screen into position once it has been aligned.

AD-A049 279 HUGHES AIRCRAFT CO FULLERTON CALIF GROUND SYSTEMS GROUP F/G 14/2
HIGH RESOLUTION, HIGH BRIGHTNESS COLOR TELEVISION PROJECTOR: AN--ETC(U)
SEP 77 P C BARON, E R CHARLES, D E SPROTBERY F33615-76-C-0040

UNCLASSIFIED AFHRL-TR-77-33(1) NL

2 OF 2
AD
A049 279

END
DATE
FILMED
2-78
DDC

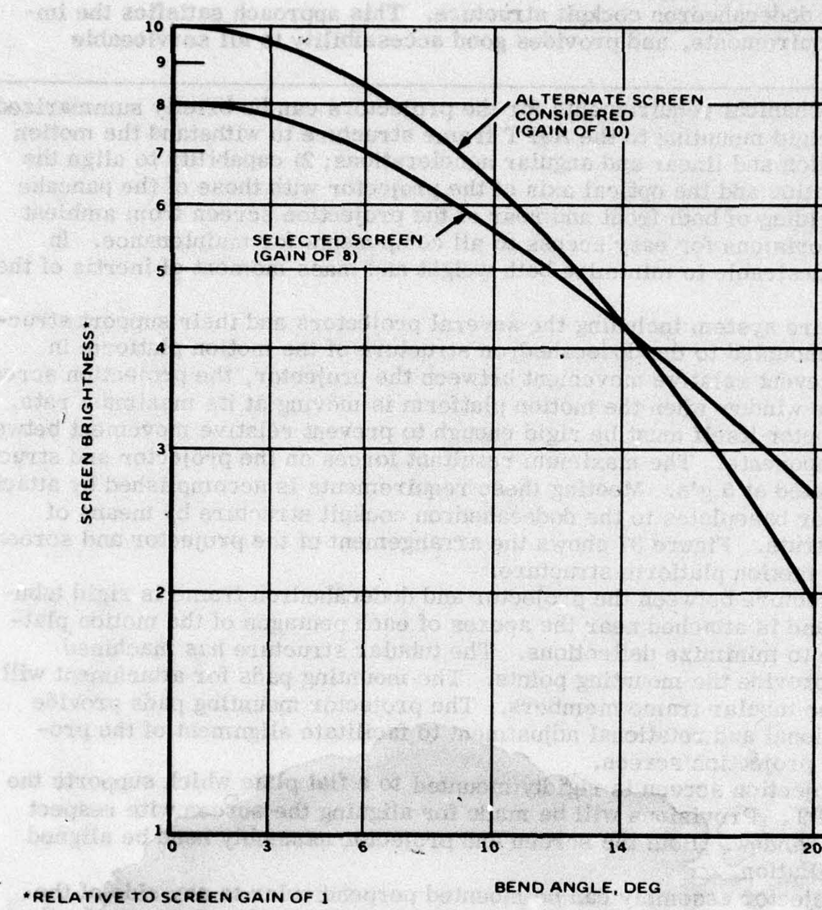


Figure 36. Goniophotometric Plot of a Typical Rear Projection Screen with a Nominal On-Axis Gain of 8 Using a Linearly Polarized Projection Light Source. The falloff at the 14° worst case bend angle is approximately 2:1.

1. DESCRIPTION OF THE SYSTEM MECHANICAL DESIGN

In a multiprojector system, the individual projectors supported by rigid honeycomb baseplates, are mounted by support struts which connect the projector baseplates to the existing ASPT dodecahedron cockpit structure. This approach satisfies the imposed dynamic requirements, and provides good accessibility to all serviceable elements.

The mechanical requirements for the projectors can be briefly summarized as follows: 1) rigid mounting to the ASPT frame structure to withstand the motion platform vibration and linear and angular accelerations; 2) capability to align the axis of polarization and the optical axis of the projector with those of the pancake window; 3) shielding of both front and rear of the projection screen from ambient light; and 4) provisions for easy access to all components for maintenance. In addition, it is desirable to minimize both weight and mass moment of inertia of the projector.

The entire system including the several projectors and their support structures must be mounted to the dodecahedron structure of the motion platform in a manner to prevent relative movement between the projector, the projection screen, and the pancake window when the motion platform is moving at its maximum rate. Also, the projector itself must be rigid enough to prevent relative movement between the optical components. The maximum resultant forces on the projector and structure are estimated at 5 g's. Meeting these requirements is accomplished by attaching the projector baseplates to the dodecahedron cockpit structure by means of rigid tubular struts. Figure 37 shows the arrangement of the projector and screen mounted to the motion platform structure.

The structure between the projector and dodecahedron frame is rigid tubular aluminum and is attached near the apexes of each pentagon of the motion platform structure to minimize deflections. The tubular structure has machined end-pieces to provide the mounting points. The mounting pads for attachment will be welded to the tubular frame members. The projector mounting pads provide axial, translational and rotational adjustment to facilitate alignment of the projector with the projection screen.

The projection screen is rigidly mounted to a flat plate which supports the CRT in the ASPT. Provisions will be made for aligning the screen with respect to the pancake window. Both the screen and projector assembly need be aligned only upon installation.

The projector assembly can be mounted perpendicular to any side of the dodecahedron pentagon facet to meet the requirement of aligning the axis of polarization of the projector to that of the ASPT pancake window. Projector orientation is then optimized to give ease of access to the electronic components. A more detailed view of the mounting scheme is shown in Figures 38 and 39.

Each of the liquid crystal projectors contains an individualized, stable alignment reference slide which can be projected through the same optics as the LCLV image. Initial mechanical alignment is made by matching the test slide horizontal line with the base of the pentagonal screen and the vertical center with the center of the screen. These alignments are made by shifting the projector's honeycomb baseplate on the pentagonal mounting frame. The unit attachment areas are then drilled and pinned in place.

Further alignment of the projectors depends on X, Y and rotational positioning of the reference slides to minimize interwindow discontinuities. After alignment, the reference slide is firmly locked into position. The final alignment step - matching the electronic images to the reference slide - is obtained electrically through size, rotation and X, Y axes adjustments.

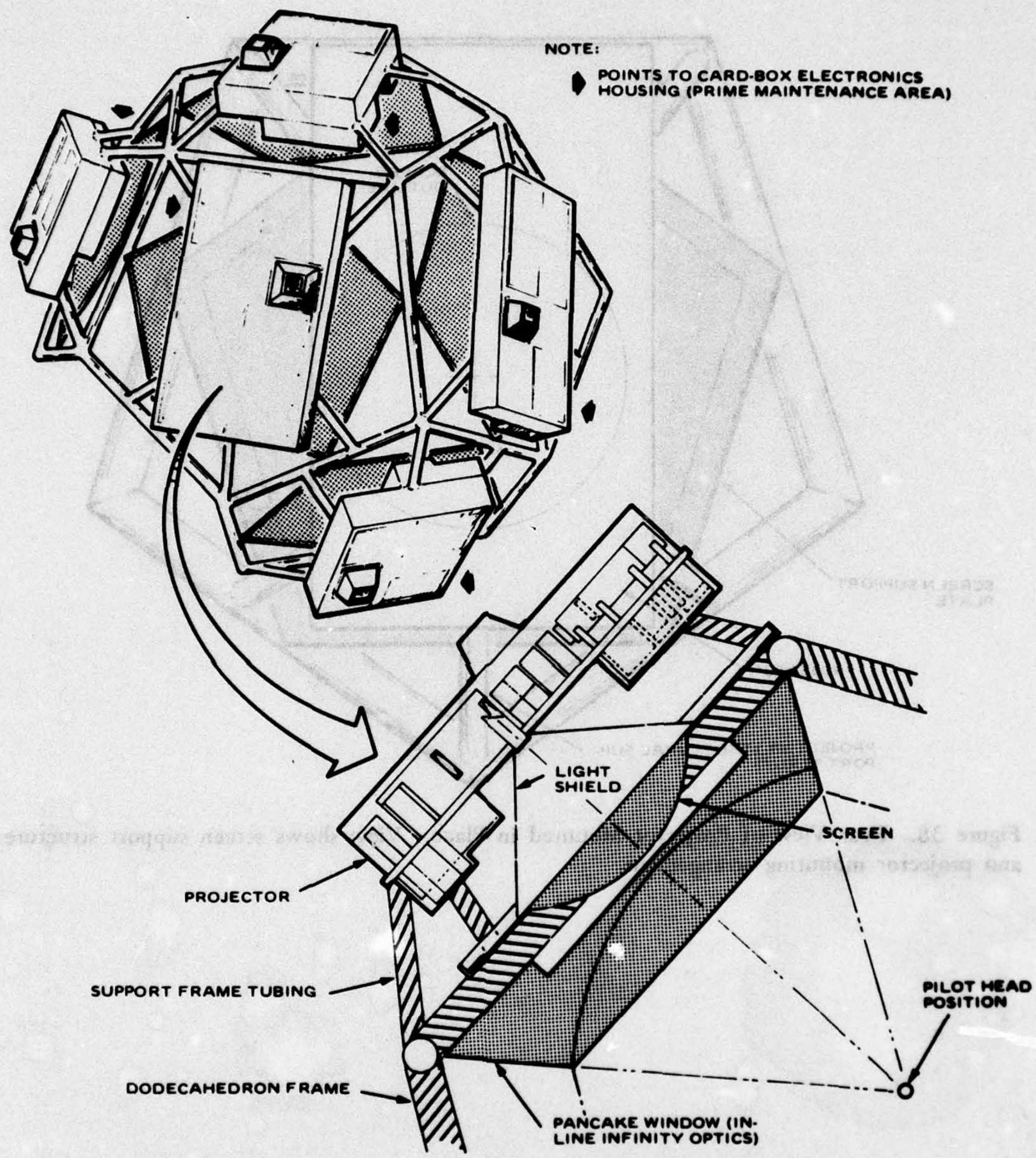


Figure 37. Overview of Multiprojector System. Mounting structs attached to the dodecahedron frame provide rigid support for the basic projector. Projectors may be perpendicular to any one of the sides of the pentagonal structure to align with the pancake window, and can be rotated to either of two positions to optimize accessibility.

1. **DESCRIPTION OF THE SYSTEM MECHANICAL DESIGN** (Continued)

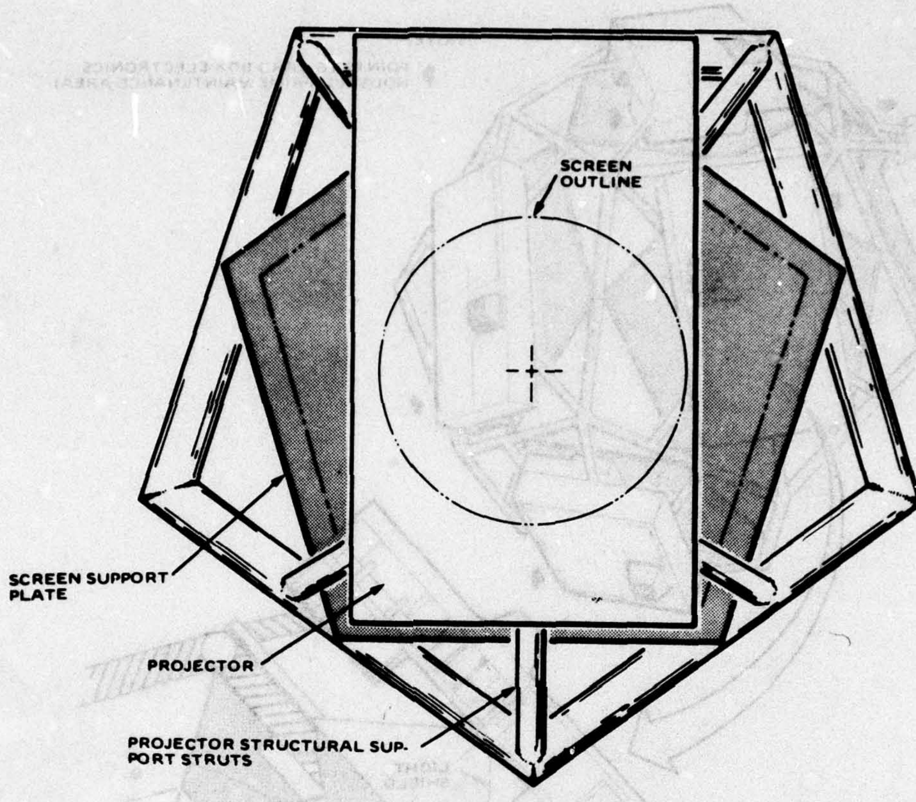


Figure 38. Rear View of Projector Mounted in Place. View shows screen support structure and projector mounting arrangement.

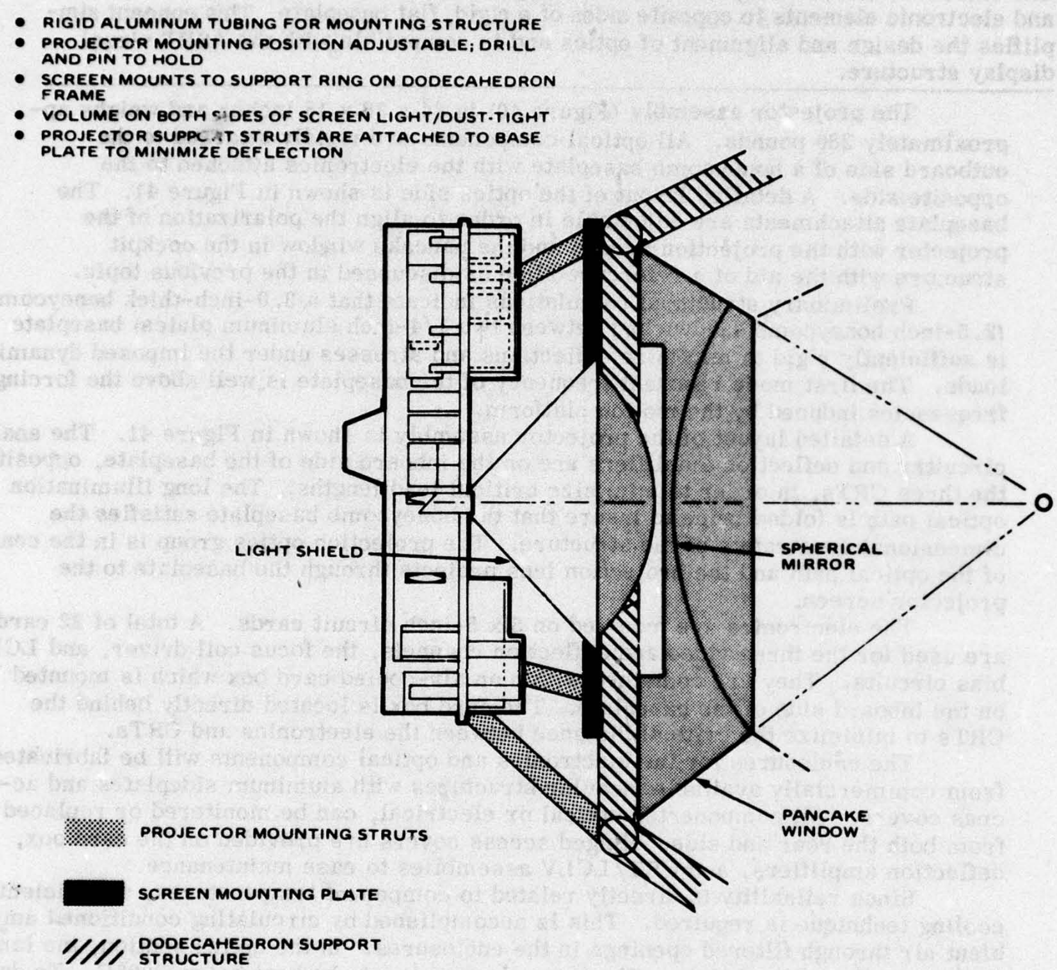


Figure 39. Detailed Side View of Projector Mounted to ASPT-Type Structure. Screen flange is fastened (in an alignable manner) to a flat ring rigidly mounted to the dodecahedron structure.

2. MECHANICAL DESIGN CONCEPT OF THE PROJECTOR

The basic mechanical design concept for the projector calls for mounting the optical and electronic elements to opposite sides of a rigid, flat baseplate. This concept simplifies the design and alignment of optics and is compatible with the ASPT visual display structure.

The projector assembly (Figure 40) is 64 x 38 x 18 inches and weighs approximately 280 pounds. All optical components are rigidly attached to the outboard side of a honeycomb baseplate with the electronics attached to the opposite side. A detailed layout of the optics side is shown in Figure 41. The baseplate attachments are adjustable in order to align the polarization of the projector with the projection screen and the pancake window in the cockpit structure with the aid of a reference slide as discussed in the previous topic.

Preliminary structural calculations indicate that a 3.0-inch-thick honeycomb (2.5-inch honeycomb sandwiched between two 1/4-inch aluminum plates) baseplate is sufficiently rigid to minimize deflections and stresses under the imposed dynamic loads. The first mode resonant frequency of the baseplate is well above the forcing frequencies induced by the motion platform.

A detailed layout of the projector assembly is shown in Figure 41. The analog circuitry and deflection amplifiers are on the inboard side of the baseplate, opposite the three CRTs, in order to minimize critical lead lengths. The long illumination optical path is folded twice to insure that the honeycomb baseplate satisfies the dimensional constraints of the structure. The projection optics group is in the center of the optical path and the projection lens projects through the baseplate to the projector screen.

The electronics are mounted on 5 x 5-inch circuit cards. A total of 22 cards are used for the three video and deflection channels, the focus coil driver, and LCLV bias circuits. They are contained within an air-cooled card box which is mounted on the inboard side of the baseplate. The card box is located directly behind the CRTs to minimize the critical distance between the electronics and CRTs.

The enclosures for the electronics and optical components will be fabricated from commercially available modular structures with aluminum sideplates and access covers. All components, optical or electrical, can be monitored or replaced from both the rear and side. Hinged access covers are provided on the card box, deflection amplifiers, and CRT/LCLV assemblies to ease maintenance.

Since reliability is directly related to component temperatures, an efficient cooling technique is required. This is accomplished by circulating conditioned ambient air through filtered openings in the enclosures. In the optics section, the lamp housing is the critical item. The lamp element has to be kept below 300°C. To do this, a small centrifugal fan is mounted to direct a stream of high velocity air directly at the element. The velocity is estimated to be 1740 ft per minute with the element temperature being 260°C. Air also has to be passed through the base of the assembly. A larger centrifugal fan drawing 90 cfm of air is therefore mounted behind the lamp assembly to draw the air along the element and through the base and exhaust it outboard. The electronics which are mounted on the opposite side of the baseplate will be cooled by their own fans. Each deflection amplifier and the card box have built-in fans with the units mounted so their exhaust air is discharged outboard. The honeycomb baseplate minimizes thermal problems by separating the electronics from the optics.

The combined noise of the fans alone is estimated at 60 dBa which, by itself, is not an objectionable level. However, several of these units surrounding an operator could be objectionable. The enclosure will attenuate the sound somewhat; acoustical foam, with a noise reduction coefficient of 0.35, will further reduce the noise level to an acceptable 49 dBa.

During the study effort, two alternative projection assembly configurations evolved; the conservative baseline approach (incorporating relay optics) and the somewhat higher risk, minimum weight approach (no relay optics). The short-path optics approach, shown in Figure 42 clearly yields a smaller, lighter weight package with greater light output, without compromising access to the electronics.

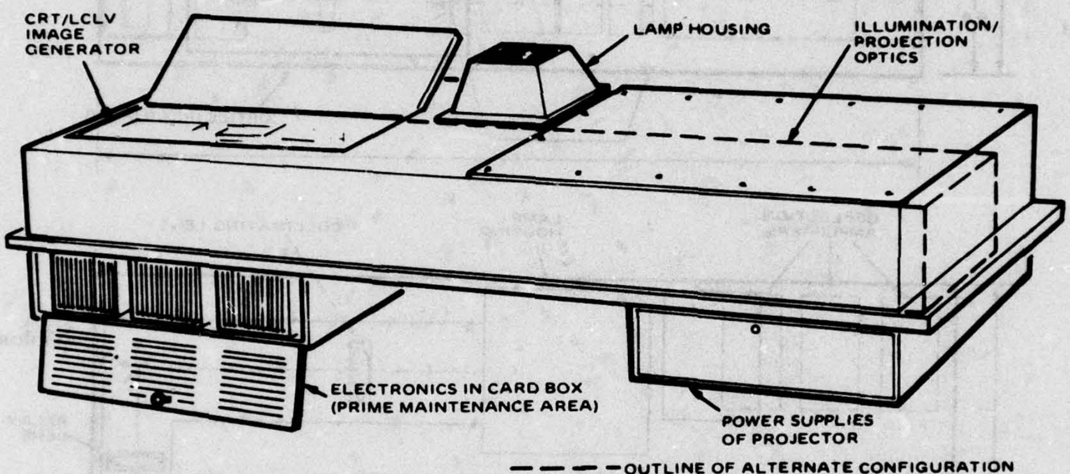


Figure 40. Side Perspective View with Two Access Doors Open

TABLE 20. PROJECTOR MECHANICAL FEATURES

- Lightweight, stiff honeycomb baseplate
- All optical components coplanar, and mounted on top; all electronics mounted below, and accessible from the side
- 90% of electronics contained in card box for ease of access
- Alternate packaging concept (without a relay in the illumination optics) cuts width by 25%, weight by 15%, and increases light output by 30%

2. MECHANICAL DESIGN CONCEPT OF THE PROJECTOR

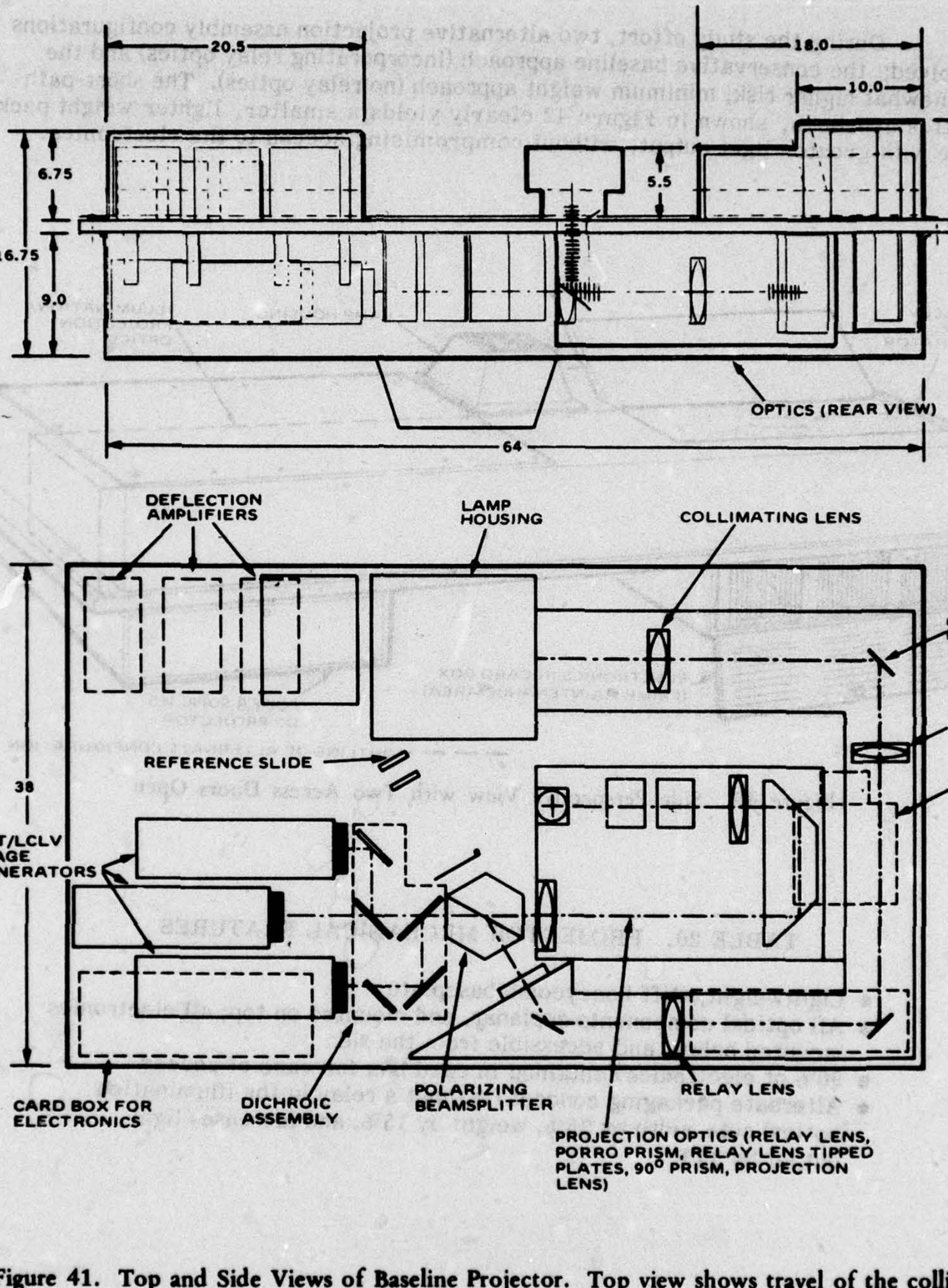


Figure 41. Top and Side Views of Baseline Projector. Top view shows travel of the collimated beam through the total system including projection optics.

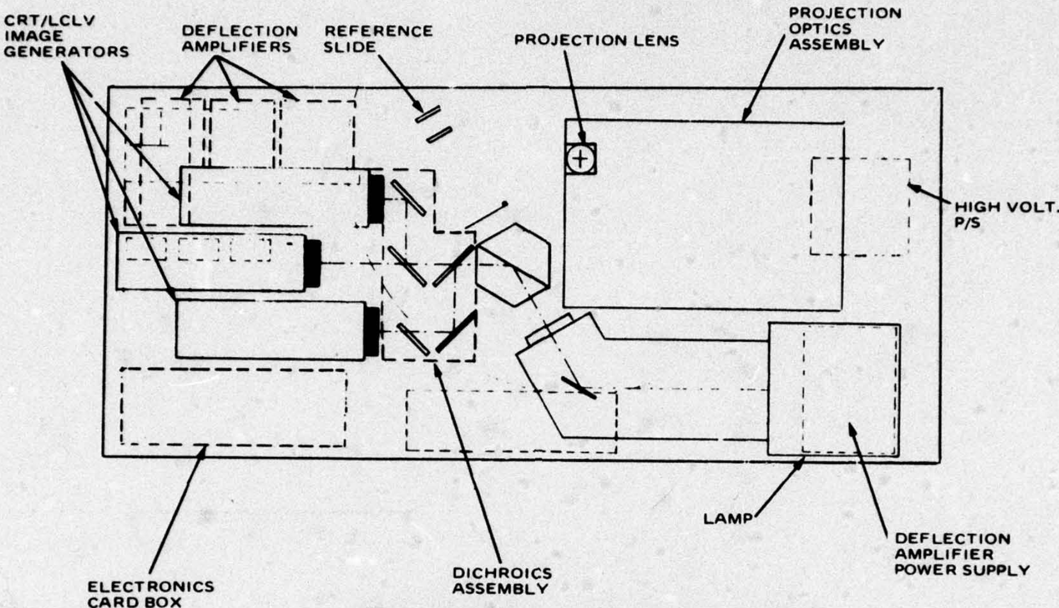


Figure 42. Alternate (Reasonably Probable) Packaging Configuration. Elimination of relay optics permits rearrangement of layout to reduce size by 25%.

Preceding Page BLANK - NOT FILMED

SECTION 7
BASELINE PERFORMANCE

1. PERFORMANCE FEATURES OF THE RECOMMENDED SYSTEM

High visual quality, system flexibility and attractive hardware characteristics of the basic projector translate directly into a high availability multiprojector full-cockpit system capable of providing the pilot with a realistic simulation of the real world (limited primarily by CIG capability).

This topic covers the performance highlights, while subsequent topics discuss the methods and data on which these performance predictions are based.

Basic Projector Features – Adequate brightness, high resolution and color fidelity are the essence of a high quality simulator capable of realistic CIG reproduction of the real world. Brightness of the system is predicated on using a 1.6 kW lamp (can be increased to 2.5 kW), and LCLV efficiency of 38 percent (expected to improve as a result of current IR&D), and a color spectrum approaching that of P22. By giving up some of the blue light (rendering the display yellowish), up to a 20 percent light increase can be realized; coupled with going to a 2.5 kW lamp and improving LCLV efficiency by 50 percent this could yield at least 2.2 times greater light output.

Although the RFP requirement specifies resolution at 1000 lines, a more commonly used measure of resolution which facilitates comparison with other techniques is the horizontal resolution in TV lines limiting (3 percent response point). The resolution at 1000 TV lines (30% MTF) can be extrapolated – with some uncertainty – to 1600 TV lines limiting. This is a resolution superior to any other technique. Furthermore, significantly higher resolution is attainable at some risk/cost.

Color capability of the projector is fair: it exceeds slightly the range of the P22 phosphor in the cyan and yellow regions, but is not capable of reproducing the blue-red (purple) region at the saturation of the P22 phosphor. Color spectrum may be selected by changing the dichroic assembly, and can be made compatible with the trichromatic holographic pancake window by sacrificing of light output. Misregistration of the three channels will be held to less than one-half line width.

Although the LCLV response time is not adequate for high speed motion (one-frame writeup) at full gray scale – see next topic for details – further R&D is expected to eliminate this shortcoming.

Flexible Interfacing Capability – By virtue of the high speed, linear deflection system employed, the projector is extremely flexible in interfacing with different systems. It has the felxibility to accommodate nonlinear sweep inputs, or it could paint multiple rasters of different types, and could even accommodate calligraphic inputs. The correction memory can also be used to shape raster or other inputs over a small range to correct for distortions if so required.

Hardware Characteristics – Semiruggedized construction, no sensitivity to orientation, lightweight, high reliability and ease of access to all replaceable components are the main hardware features. The first three mean that the projector is ideally suited for operation on a motion platform, while the last two translate into high equipment availability. The MTBF quoted in Table 21 (8000 hours) is based on projector mounted hardware only (does not include low voltage and lamp power supplies). It is an impressively high number, attributable to the high sensitivity of the light valve which in turn means low CRT voltage which permits use of a low power deflection system.

Multiprojector System Features – Major features of the full-up system are an extension of the basic projector performance. They include 1) a wide field-of-view, mosaicked display with minimal discontinuities across adjacent

windows; 2) compatibility with motion platform at the system level, and 3) high availability at the system level.

The techniques required to insure good color registration are inherently capable of good distortion control to achieve minimum image discontinuity between adjacent windows. Carefully prepared reference slides are incorporated in each projector; these are initially aligned slides to which the video generated image of all three channels can be aligned individually for each projector. This is an important maintainability feature; it reduces the interaction among the individual projectors and thus greatly simplifies the job of realigning the system, should this be necessary. High availability is also enhanced by the high system MTBF (1130 hours, achieved by a redundant central power supply configuration), good accessibility, and a central minicomputer with disc storage which supplies test patterns (for system verification, fault diagnosis and alignment) and aids the task of setting up the correction memories.

TABLE 21. KEY PERFORMANCE FEATURES OF RECOMMENDED PROJECTOR/SYSTEM

Basic Projector Features	
High Visual Quality	• High brightness (with growth) • 1500 TV lines limiting resolution (with growth) • Full color (similar P22 spectrum) • Response time nearly adequate
Interface Flexibility	• Linear deflection • Correction memory for distortion compensation
Attractive Hardware Characteristics	• Weighs 280 lbs (240 lbs alternate) • Ruggedized to take shock • 8000 hour MTBF • All components easily accessed
Multiprojector System Features	
Accurate Mosaicking	• Brightness variation across edges <±17.7% (rms) • Interwindow discontinuity <1%
High Availability	• System mission-critical MTBF of 1130 hours • Wide range of maintainability features • Central minicomputer + dual discs (test patterns, diagnostics, computer aided alignment) • Reference slide – system alignment on a projector-by-projector basis
Compatibility With Motion	• Rigid mounting of projectors to dodecahedron frame • Total weight on platform is approximately 2600 lbs (includes support structure)

2. PERFORMANCE CAPABILITY VS SPECIFIED REQUIREMENTS

Except for brightness and color uniformity (which is *cosmetically significant* but operationally unimportant) and speed of response, the recommended projector complies with all performance design goals. Current research and development work will improve the response speed.

The RFP requirements and the performance characteristics (based on analyses in this section) of the recommended system are compared in Table 22. Critical interpretations for some of these parameters, and the reasons for not fully complying with some others are discussed below.

Brightness – Screen brightness requirement is 480 fL. Since this is a screen gain dependent number, it is important to specify a more basic measure – light output usable by polarizing pancake window – to evaluate projector performance. For polarized light, assuming 1) a screen with a gain of 8.0 (<2:1 light falloff with 6-inch pilot head motion), 2) a screen depolarization factor of 5%, and 3) a screen size of 6.75 ft^2, a minimum 216 lumens are required to produce a display of 6 fL brightness to the pilot.

Note that these calculations are based on a flat spectrum pancake window. Spectral characteristics (which were made available to Hughes) of one of the ASPT pancake windows show rather poor efficiency in the blue region. The ASPT pancake windows were designed by Farrand to operate with a P1 phosphor CRT; there was no need therefore to keep a wide spectrum. It is assumed that a broader spectrum will be provided for a multicolor system.

Brightness Variation – Because of the number of projector components which affect brightness uniformity (lamp, illumination system, LCLVs, projection optics, screen), meeting the RFP goals does not appear cost-effective (see Topic 2-2, requirements analysis). Most of the ± 25% brightness variation is expected to be low spatial frequency (i.e., gradual variation across the screen) and therefore not easily detected by the pilot. Whether the edge-to-edge variation of 35% (or less) is noticeable depends on whether joints are used to segregate the windows. If they are used (which appears likely),the 30% brightness difference recommended will be barely perceptible. Brightness variation as a function of pilot head motion is due to screen gain. Falloff may be traded off for light output (see Topic 5-3).

Contrast. Contrast ratio attainable with a 30:1 contrast LCLV is 20:1. If LCLV contrast is raised to 40:1 (this looks to be achievable), contrast ratio will be raised to nearly the required 25:1.

Distortion – Because of the features incorporated to meet color registration of 0.06%, it is expected that distortion will be much less than the 1% required.

Color Variation – A slight variation in color across screen and with intensity is expected, and is primarily attributable to the LCLV characteristics. Meaningful data on color variation are unavailable at this time. When the LCLV is put into production, the resulting color variation should be barely perceptible.

Response – The current LCLVs provide a response close to adequate for commercial television, but not sufficiently fast to accommodate the single-frame writeup capability required for a high-speed motion operation. The feasibility of a faster response cell with the CdS photoconductor has been established, and response will be improved with further research and development (R&D). A current R&D program to change the LCLV photoconductor material will essentially eliminate this problem.

Display Configurations. The pentagonal on spherical, rectangular on spherical, and rectangular on flat screen configurations are feasible. System performance for these configurations is summarized in Topic 7-13.

TABLE 22. COMPARISON OF LCLV COLOR PROJECTOR CHARACTERISTICS WITH RFP REQUIREMENTS

Parameters	RFP Requirements	Characteristics of Recommended System
Image Parameters		
Brightness	445 lumens, or 216 lumens (polarized)	>216 lumens (polarized)
Brightness variation		
Across screen	<25%	<±25%
Edge-to-edge	<12%	<35%
With pilot head motion*	Not specified	Maximum of -50% with 6" head motion
Contrast ratio	25:1	20:1
Resolution: Center	1000 TVL @30%	1000 TVL @ 30%
Edge	750 TVL @35%	750 TVL @ 37%
Geometric Distortion	<1%	<1% (0.5%)
Interwindow discontinuity*	Not specified	1.0%
Color registration*	Not specified	0.06%
Color: Response	Same as P22	Similar to P22
Variation across screen	Not visible when directly viewed	Slight variation
Shift with screen intensity	Not visible when directly viewed	Slight variation
Persistence	No color shift	See text
	Compatible with 30 frames/sec and high speed motion	
Electrical Parameters		
Video Input	EIA Std RS 343, 1023 line, 1:1 aspect ratio	RS 343, 1023 line, 1:1 aspect ratio
Image drift	< 0.5%	0.1%
Alignment	Center, roll and size image	Center, roll and size alignment capability
Video bandwidth	20 MHz @±1 dB, t_r = 25 ns	20 MHz @±1 dB, tr = 15 ns
Interface	Fixed element rate CIG	Fixed element rate CIG
Special Requirements		
Motion platform		Will meet
Acceleration-forward-lateral, heave	±0.69g ±0.89g	
Angular acceleration	$\pm 50^o/s^2$	
Weight	Minimize platform weight	<300 lbs (projector)
Cabling	Minimize cabling	
Life: Lamp	Estimated life of major components	1500 hours
CRT		3000 hours
LCLV		2000 hours
Reliability (MTBF)	–	8000 hours
Optical Requirements		
Mapping correction	$90^o \times 90^o$ projection, ASPT-compatible	$90^o \times 90^o$ projection, ASPT-compatible
Display configurations	Pentagonal on spherical screen	Feasible
	Rectangular on spherical screen	Feasible
	Retangular on flat screen	Feasible

*Study-developed requirement

3. LIGHT OUTPUT/BRIGHTNESS CAPABILITY OF PROJECTOR

The recommended projector supplies more than 480 fL of effective highlight brightness at the projection screen, using a tradeoff-optimized design. A number of low risk approaches could be implemented to increase light output by as much as a factor of 1.5.

ASPT requirements call for a highlight brightness of 480 fL on the projection screen. The components of the optical subsystem were carefully designed or chosen to meet the system requirement. Figure 43 identifies the optical efficiency of each component in the optical chain. This combination of component efficiencies is the result of the tradeoff study which optimized the design in terms of equalizing risk/cost (Topics 5-1 through 5-3).

The 1.6 kW xenon arc lamp delivers 35,400 lumens to the illumination group which has an efficiency of 22%. The light is polarized by the MacNeille prism as it proceeds to the LCLVs, is reflected at the LCLVs, and is analyzed by the prism as the image is passed to the projection optics group. The MacNeille prism has a two-pass efficiency of approximately 45%.

Before reaching the LCLVs the "S" polarized light from the MacNeille prism is split into three beams, by the dichroic beamsplitter plates. Each beam of light is one of the three primary colors. A trimming filter may be used in each channel to control the channel's intensity and the primary color's purity. The optical efficiency of 29% used for this group is based on tests of a non-TV cell and takes into account the spectral characteristics of the xenon light which has infrared and ultraviolet light filtered out before it enters the illumination group. This efficiency factor also assumes that no filter is used in the blue channel, and that the red and green channels are filtered to decrease their intensity so that when added, the three channels produce a white that is close to an Illuminant C white. Note that the 29% figure is based on analysis of the CX (non-TV) LCLV, and may change slightly for the TV cells.

The 38% efficiency factor used for the LCLV is based on results of the LCLV tests, and assumes operation to only 80% of peak brightness to ensure that the LCLV would be operated on the linear portion of its gamma curve. The projection optics group has a 59% efficiency with the high efficiency anti-reflection coatings (HEA) used.

The overall optical efficiency of 0.64% for the optics subsystem can be calculated by multiplying the efficiencies given in the figure. Thus 0.64% of the 35,400 lumens from the xenon arc lamp, or 226.5 lumens, will be delivered to the projection screen.

A gain of 8 screen with an area of 6.75 sq. ft. and with a depolarization factor of .05 presents an image of the following brightness to the pancake window:

$$B_S = \frac{226.5 \times 8}{6.75} \times (1-0.05) \cong 254 \text{ fL (polarized)}$$

The required brightness in the screen is 480 fL of nonpolarized light. Since this is equivalent to 240 fL of polarized light, baseline projector exceeds the RFP requirement.

<u>Growth</u> – As discussed in the section on System Trade-offs a number of different ways of increasing light output are possible. The most significant of these are listed in Table 23, along with anticipated gain factor. In most cases, some other performance parameter (color, lamp life, etc.) is affected, but not seriously.

It is worth noting that if the first two low risk approaches are incorporated, light output is raised by a factor of 1.5 from its present value. Elimination of the

relays in the illumination optics (considered to be feasible) raises this factor to nearly 2 (1.98). Thus there is significant growth possible without depending on either a higher efficiency LCLV or a higher powered lamp.

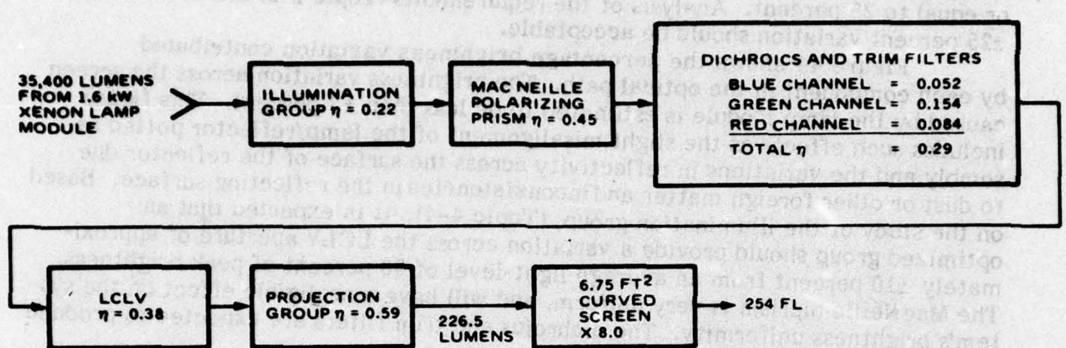


Figure 43. Optical Efficiencies of Optics Subsystem Components for Baseline Approach. Overall optical efficiency = 0.64% with 35,400 lumens input yields well over the required 216 lumens.

TABLE 23. APPROACHES TO PROVIDE INCREASED LIGHT

Approach	Gain (estimated)	Comment
Increase screen gain to 10	1.25	Slight increase in light falloff and differential brightness
Unbalance primaries	1.2	Display color shifts from white toward yellow
Eliminate relays in illumination system	1.32	Requires change in lamp reflector design; slight risk
Increase LCLV efficiency to 50% in blue channel	1.31	Depends on success of ongoing LCLV IR&D; high probability of success within 12 months
Increase lamp power to 2.5 kW	1.3-1.5	No testing on 2.5 kW lamp, performance risk, plan to test

4. PROJECTOR AND INTERWINDOW BRIGHTNESS UNIFORMITY

A systematic analysis of projector brightness uniformity results in a predicted value of ±10 percent plus ±13.7 percent rms (or less than ±25 percent). Improving this figure is feasible, but would compromise system maintainability.

Brightness Uniformity – The ASPT requirements for uniformity are quite stringent: the brightness variation across the screen is required to be less than or equal to 25 percent. Analysis of the requirements (Topic 2-2) indicates that a ±25 percent variation should be acceptable.

Figure 44 shows the percentage brightness variation contributed by each component in the optical path. The brightness variation across the screen caused by the lamp module is estimated to be less than ±3 percent. This figure includes such effects as the slight misalignment of the lamp/reflector potted assembly and the variations in reflectivity across the surface of the reflector due to dust or other foreign matter and inconsistencies in the reflecting surface. Based on the study of the illumination group, (Topic 4-4), it is expected that an optimized group should provide a variation across the LCLV aperture of approximately ±10 percent from an average light-level of 90 percent of peak brightness. The MacNeille biprism is very uniform, and will have a negligible effect on the system's brightness uniformity. The dichroics and trim filters are expected to produce less than ±1 percent variation in brightness.

CRTs can produce small area brightness variations of ±3 percent and large area variations of as much as ±7 percent. These variations are caused by changes in spot size, variation in the thickness of the CRT's fiber optic faceplate, and variations in phosphor thickness. Once the manufacturing methods technology program is completed, the LCLV will have a predicted random variation of ±10 percent. The nominal falloff in the projection optics is 0; however, some variation (estimated at 2 percent) can be expected. The selected type screen is expected to have much less than ±5 percent variation in screen gain across the usable area of the screen.

All the brightness variations indicated in the figure are random except the systematic variation of ±10 percent due to the illumination group. Superimposed on the systematic variation is a root-mean-square random variation of ±13.7 rms. The worst case error is the sum of all errors of either source: 3 + 1 + 7 + 10 + 2 + 5 + 10 = ±38 percent.*

It should be noted that if the ±10 percent plus ±13.7 percent rms variation is unacceptably high, or if some of the component tolerances are too expensive to achieve, brightness uniformity can be improved to nearly meet the RFP specified 25 percent by providing electronic area-dependent intensity compensation. This compensation would use basically the same logic as the deflection correction memory, and should be implementable at minimum cost. Because of the extra alignment requirement it implies, this technique is not incorporated in the baseline system.

Interwindow Edge-to-Edge Brightness Uniformity – The RFP required interwindow uniformity is 12 percent; analysis of this requirement in Topic 2-2 shows that ±25 percent is a more realistic requirement.

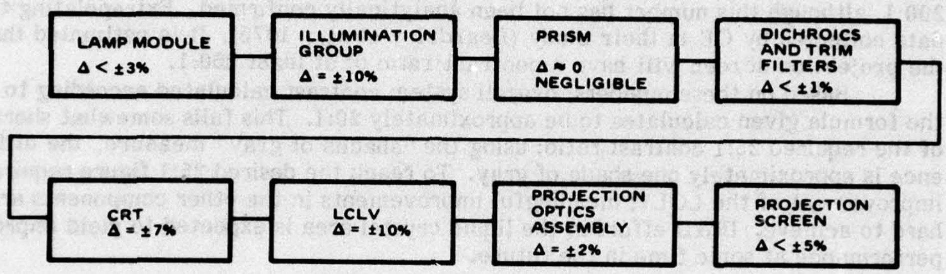
Several factors affect this figure. First, there is the random variation in brightness uniformity on each screen (±13.7 percent rms). Second, while the systematic, radius-dependent light falloff of the projection optics should produce only the variation due to radial distance of the pentagon sides and corners from the center of the screen, in fact there will be variations between light falloff patterns that

*Both numbers are based on several assumptions, and should be treated accordingly.

will contribute an estimated 10 percent (random) to the edge-mismatch between windows. Finally, there is a difference in brightness due to differential aging of the lamps between periodic alignments (when the windows are equalized on brightness); this is estimated to be 2 percent.

Based on these numbers and using the formula shown in Figure 44, the rms interwindow brightness variation will be $\sqrt{(188 + 10^2 + 2^2)} = \pm 17.1$ percent rms, or 34.2 percent rms. Worst case maximum error will be $(3 + 1 + 7 + 10 + 2 + 5 + 10 + 2) = \pm 40$ percent.*

Note that the comments regarding use of an electronic area-dependent intensity compensation method for improving brightness uniformity can reduce this number to an undiscernible level.



RANDOM BRIGHTNESS VARIATION

	Δ	Δ^2
LAMP MODULE	±3%	9
DICHROICS & TRIM FILTERS	±1%	1
CRT	±7%	49
LCLV	±10%	100
PROJECTION OPTICS	±2%	4
SCREEN	±5%	25
	±28%	$188 = \pm \Sigma\Delta^2$

RMS RANDOM VARIATION = $\sqrt{\Sigma \Delta^2} = 13.7\%$

SYSTEMATIC BRIGHTNESS VARIATION

	Δ
ILLUMINATION GROUP	±10%

Δ = BRIGHTNESS VARIATION

Figure 44. System Components Contributing to Brightness Variations Across Projection Screen

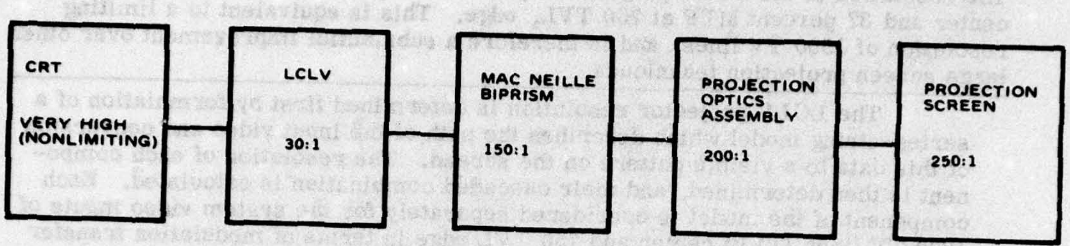
*Both numbers are based on several assumptions, and should be treated accordingly.

5. IMAGE CONTRAST

System contrast is estimated to be 20:1, slightly short of the required 25:1. IR&D efforts on the liquid crystal light valve are expected to yield improved performance.

The ASPT design requirements call for a contrast ratio of 25:1. Figure 45 shows the components that affect system contrast and the values assigned to each one. The CRT has a very high contrast ratio and will not be a limiting factor in system contrast. The fused silica MacNeille biprism (currently being delivered to Hughes) was specified to have a contrast ratio of at least 100:1 realistically, contrast is expected to be a minimum of 150:1. Its contrast ratio is determined by its polarization ratio (Tp/Ts or Rs/Rp). Based on the results of tests conducted on television cells, it appears that the LCLV should be able to achieve a 30:1 contrast ratio when used in light of the primary color for which it is optimized. The projection optics assembly should have a very high contrast ratio of greater than 200:1, although this number has not been analytically confirmed. Extrapolating the data collected by GE in their study (Beardsley et al., 1975), it is estimated that the projection screen will have a contrast ratio of at least 250:1.

Based on these numbers, overall system contrast calculated according to the formula given calculates to be approximately 20:1. This falls somewhat short of the required 25:1 contrast ratio; using the "shades of gray" measure, the difference is approximately one shade of gray. To reach the desired 25:1 figure requires improvement of the LCLV; meaningful improvements in the other components are hard to achieve. IR&D effort in the liquid crystal area is expected to yield improved performance at some time in the future.



	CONTRAST RATIO (C_x)	Y_{Cx} (%)
LCLV	30:1	3.33%
MAC NEILLE BIPRISM	150:1	0.67%
PROJECTION OPTICS	200:1	0.50%
PROJECTION SCREEN	250:1	0.40%
OVERALL SYSTEM CONTRAST RATIO =		4.9% = ≅ 20:1

$$\frac{1}{C_{SYSTEM}} = \sum_{x=1}^{4} \frac{1}{C_x}$$

Figure 45. Calculation of Overall LCLV Projection System Contrast Ratio

6. CALCULATED RESOLUTION OF THE LCLV PROJECTION SYSTEM

The resolution of the LCLV projection system is 30 percent MTF at 1000 TVL, center and 37 percent MTF at 750 TVL, edge. This is equivalent to a limiting resolution of 1500 TV lines, and is therefore a substantial improvement over other large screen projection techniques.

The LCLV projector resolution is determined first by formulation of a series-string model which describes the path of the input video and conversion of this data to a visible pattern on the screen. The resolution of each component is then determined, and their cascaded combination is calculated. Each component of the model is considered separately for the system video inputs of 1000 TV lines (TVL) center and 750 TVL edge in terms of modulation transfer function (MTF). For this purpose, MTF is a highly useful tool for analyzing resolution since multiplication of the individual component MTFs yields the overall MTF. The system resolution model shown in Figure 46 also includes the MTF of each component at the center at 1000 lines and at the edge at 750 lines. The source of the data which describe the primary characteristics of each component is either a design requirement, manufacturer's data or laboratory measurement.

The assumption underlying all these calculations is that the system is essentially a linear one, with all elements having gaussian MTF. The analysis will yield only an approximation of the system resolution because: 1) both the CRT and the LCLV are nonlinear devices, and 2) the amplifier is two pole and drops off more rapidly than Gaussian while the LCLV response is higher than the Gaussian curve. This approach will yield a very conservative estimate; system resolution is expected to be significantly higher than calculated.

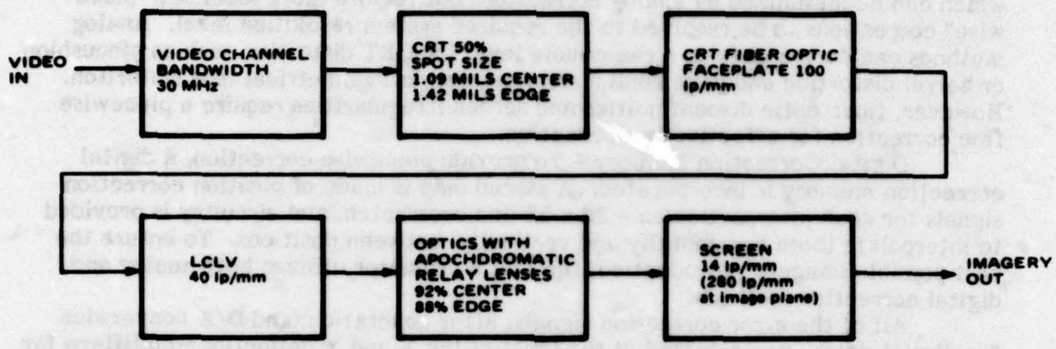
The video channel bandwidth is a function of the bandwidths of the video preamplifier, the video amplifier and the gamma correction circuit. A video preamplifier presently in use has a 75 MHz bandwidth and serves as an interface matching network for the input video as well as a buffer to drive the main video amplifier. In combination with the video amplifier and gamma correction an overall video bandwidth of 30 MHz with a pulse rise and fall of 15 nanoseconds is readily implemented.

The characteristics of the CRT were verified by measurement. Those of the projection screen were obtained from the supplier's data on each component. The CRT 50 percent spot size at the required light output of 150 to 200 footlamberts for the best CRT tested to date is 1.3 mils. Optimization of the design should provide the 1.1 mil spot at the center and the 1.42 mils at the edge required to meet system design requirements (see topic on System-Level Resolution Tradeoffs in Section 5). From the Kollmorgen study, the predicted resolution of the apochromatic projection optics is 92 percent and 88 percent MTF at the center (at 1000 lines) and edge (at 750 lines), respectively. The projection screen has a limiting resolution of 14 line pairs per mm (lp/mm) at the screen, according to the manufacturer's data sheet. Referenced back to the object plane through the lens this means a limiting resolution of 280 lp/mm, or 99 percent MTF.

Measurements were performed in 1975 on the fiber optic faceplates and the LCLV to determine limiting resolution. A single plate measured had 115 lp/mm limiting. The worst case for two plates in contact was measured as 74 lp/mm. Based on this the figure 100 lp/mm was selected for the CRT fiber optic faceplate. (Note: the LCLV measurement includes the effect of one of the fiber optic plates.) The typical limiting resolution of the liquid crystal light valves measured was 40 lp/mm at the required light output.

Based on the above data, the MTF for the system components in the model can be determined. A summary of the tabulated values is shown in Figure 46, with the calculated results compared to the specificaticn requirements. Calculations are based upon a 1.6-inch raster size. It is assumed that degradation due to cable losses, imperfect alignment, noise, CRT spot jitter and fiber optic imperfections will be minimized.

Table 24 summarizes how system resolution can be improved further. If all of the approaches listed in the table are implemented simultaneously, a total resolution increase of nearly 50 percent is realizable. Through further research and development this appears very feasible. Note again that since these calculations are based on sine-wave MTF figures, the MTF with a square-wave CIG input is expected to exceed calculated values by a wide margin.



	VIDEO	CRT	F/O	LCLV	OPTICS	SCREEN	SYSTEM	SPEC
CENTER % MTF @ 1000 TVL	80	57	96	75	92	99	30	30
EDGE % MTF @ 750 TVL	88	59	97.5	85	88	99	37	35

Figure 46. Series Model for Horizontal Resolution. The system MTF at 1000 lines (center) and at 750 lines (edge) is a product of the series model component MTFs at these two spatial frequencies.

TABLE 24. APPROACHES TO IMPROVING SYSTEM RESOLUTION

Approach	System Resolution Increase*	Comments
Decrease CRT Spot Size to 0.9 mils	**20%**	**• Appears practical (higher CRT anode voltage)**
Increase Video Bandwidth to 50 MHz	**15%**	**• Requires wide-band open-loop video amplifier**
Increase LCLV Resolution to 50 lp/mm	**11%**	**• Higher cost (lower yield)**

***With respect to baseline**

7. TECHNIQUES THAT MINIMIZE PROJECTED IMAGERY DISTORTIONS AND DISCONTINUITIES

A stable predistorted reference slide and a digital correction memory to implement piecewise correction of the displayed rasters are the key concepts in achieving lower-than-required distortion, interwindow continuity, and color registration characteristics.

The specified geometric distortion through the display optics is 1% or less. However, for two adjacent projected displays, this translates to a 2% misalignment error possible at screen edges, or nearly 3/4 inch. To provide good color registration in a single projector, the channel-to-channel registration should be less than 0.05%. To provide good color purity and interwindow image continuity, both misregistration and distortion must be minimized.

The distortion in the projector system results from a number of factors which can be minimized by analog corrections but require more localized "piecewise" corrections to be resolved to the required system resolution level. Analog methods can compensate to a reasonable level for CRT distortion such as pincushion or barrel distortion and yoke nonlinearity, as well as symmetrical lens distortion. However, fiber optic discontinuities and screen irregularities require a piecewise fine correction for effective compensation.

Digital Correction Memory – To provide piecewise correction, a digital correction memory is incorporated. A stored map is made of position correction signals for each intersection on a 32 x 32 line crosshatch, and circuitry is provided to interpolate (both horizontally and vertically) between positions. To ensure the best possible imagery reproduction, the LCLV projector utilizes both analog and digital correction methods.

All of the error correction signals, after generation (and D/A conversion for digital data), are summed at the input of the X and Y deflection amplifiers for each channel as analog compensation waveforms. Linearity correction is performed to produce horizontal and vertical lines which are straight in an average sense. Orthogonality correction is performed to make these lines cross at right angles. Piecewise correction is effective in making a fine correction on a point-by-point basis on the 32 x 32 matrix. These techniques provide the means of accurately aligning the electronic raster to an optical reference.

Stable Predistorted Reference Slide. This key concept is incorporated to minimize both distortion for a single projector and interwindow discontinuity: the capability of each projector to project a reference slide using the same projection optics as the three television channels. The slide can be projected on the screen simultaneously with the color raster generated image, and can, after initial alignment of the system, be used as a reference for its own projector. This eliminates the interaction between adjacent windows (projectors), and allows the system to be aligned for minimum interwindow discontinuity by simply aligning each projector to its own reference slide. The reference slide is made of a stable material, and is prepared to eliminate distortions caused by the projection optics. The latter is achieved by exposing the slide (when making it) to a precise reference crosshatch on a curved screen using the same projection lens as the one used in the projector, and using a stable base material which does not shrink in processing.

Multiprojector System Alignment Procedure – To explain the approach to correction of distortion in a multiprojector system, the procedure for initially aligning the system is described here. To begin system alignment, the projectors are mechanically aligned using the projected reference slide first to align the horizontal lines parallel to the base of the pentagonal screen, and then to align the axis of polarization of output light with that of the pancake window, and finally to align the

pattern center with the screen center. Each of the projector reference slides is then adjusted (by slide rotation and slide XY positioning) to achieve the best possible alignment of pattern edges. The crosshatch pattern is then selected for display through the green channel, and the raster is corrected for linearity, orthogonality, and size with respect to the reference slide using the analog correction adjustments. Next, the green channel is piecewise corrected by the operator using the digital correction memory. Finally the red and blue channels are matched to the green (with the reference slide blocked) using both analog and digital correction to minimize color misregistration.

Since the accuracy of the reference slide should be to within 0.15% and channel alignment to the reference slide is to the accuracy of one display element, or 0.1%, and allowing 0.05% for drift, the maximum position error should be 0.3% for one projector. Worst case alignment of adjacent projectors doubles this error to a maximum of 0.6%, or less than 0.5 inch discontinuity at screen edges. Conservatively, the figures 0.5% for distortion and 1% for interwindow discontinuity should be easily obtained.

Figure 47 shows examples of crosshatch misalignment and discusses details of piecewise correction procedures.

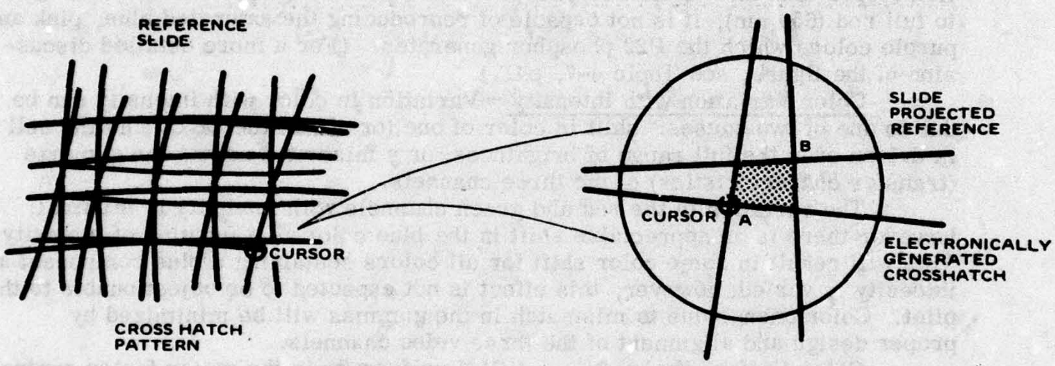


Figure 47. Illustration of Alignment Procedure. Moving cursor from A to B and entering new position loads correction signals into the digital correction memory, and realigns the raster to cause the slide projected and electronically generated crosshatch intersections to superimpose. Computer interpolation of correction points entered will reduce the number of points to be entered to realign the system from a thousand to as few as one (for the case of compensating for a simple offset).

8. COLOR AND RESPONSE TIME PERFORMANCE

The color response of the system approximates that of P22 phosphor with color variation across the screen a direct function of LCLV uniformity. The area of persistence/response requires further investigation.

ASPT requirements call for a color range that is the same as P22 phosphor used in color television receivers. Furthermore, there should be no visible color variation across the screen when the screen is viewed directly, no visible color shirt when the light output intensity is modulated, and no color shift due to persistence when the visual scene contains high speed motion.

The recommended baseline approach for meeting these requirements is to use red and blue dichroic reflectors that have 50% reflectance at approximately 585 nm and 490 nm respectively. This approach does not use a trim filter in the blue channel since it is the least efficient channel, and it is desired to have maximum light output.

Color Range – The spectral characteristics of the baseline LCLV projector are shown on the CIE diagram, Figure 48. The baseline system used 60 nm wide filters in the red, green and blue channels to achieve the required light output with a 1.6kW lamp. The vertices of the triangle defining the color range are the estimated centroids of the locus of points representing colors over the full range of intensities. Although the projector is capable of higher saturation colors than that of the P22 phosphor for colors ranging from blue (485 nm) to full red (650 nm), it is not capable of reproducing the saturated blue, pink and purple colors which the P22 phosphor generates. (For a more detailed discussion of the figure, see Topic 4-7, p41.)

Color Variation with Intensity – Variation in color with intensity can be due to one of two causes: shift in color of one (or all) of the LCLVs as the cell is driven over the full range of brightness; or a mismatch among the gammas (transfer characteristics) of the three channels.

The variation in the red and green channels with intensity is minimal; however there is an appreciable shift in the blue color as a function of intensity. This will result in some color shift for all colors containing a blue component as intensity is varied; however, this effect is not expected to be objectionable to the pilot. Color change due to mismatch in the gammas will be minimized by proper design and alignment of the three video channels.

Color Uniformity by Area – LCLV uniformity is the major factor controlling color variation across the projection screen. It is expected that once a currently planned manufacturing methods technology program for the LCLV is completed, uniformity will be better than ±10% across the aperture. It is expected that this variation will not cause a visible color variation on the screen. If color variation across the screen is objectionable, then it may be necessary to incorporate area dependent intensity compensation into the system. Since the logic to implement area-sensitive deflection correction already exists, adding video area compensation can be implemented at minimal cost, although it does require additional effort to align the projector.

Persistence/Response – The RFP requirement for persistence (response) states the need to accomodate a 30 Hz frame rate and high speed motion of the visual scene. This implies the following:

- No flicker should be observable with a 30 Hz interlaced raster.
- The projector should be capable of writing up the display image in a single frame to perform adequately in high roll, pitch, and yaw rate environments.
- After-image (decay) must be minimized.

Response of the LCLV is sufficiently fast that no image persistence is visible with live (commercial) 525 line TV. However, the cells tested heretofore have exhibited inadequate response to single-frame excitation required for high speed motion.

Although single-frame writeup can be accomplished by overdriving the LCLV, this will result in loss of gray scale. Whether loss of gray scale under conditions of rapid motion is acceptable or not is conjectural – it is quite possible that some dynamic intensity compensation during high speed motion will result in acceptable performance. Nevertheless, it is clearly desirable to avoid this problem altogether by improving the response time of the LCLV (this has been shown to be feasible at the Hughes Research Laboratories). It is therefore recommended that a program to overcome this LCLV deficiency be initiated.

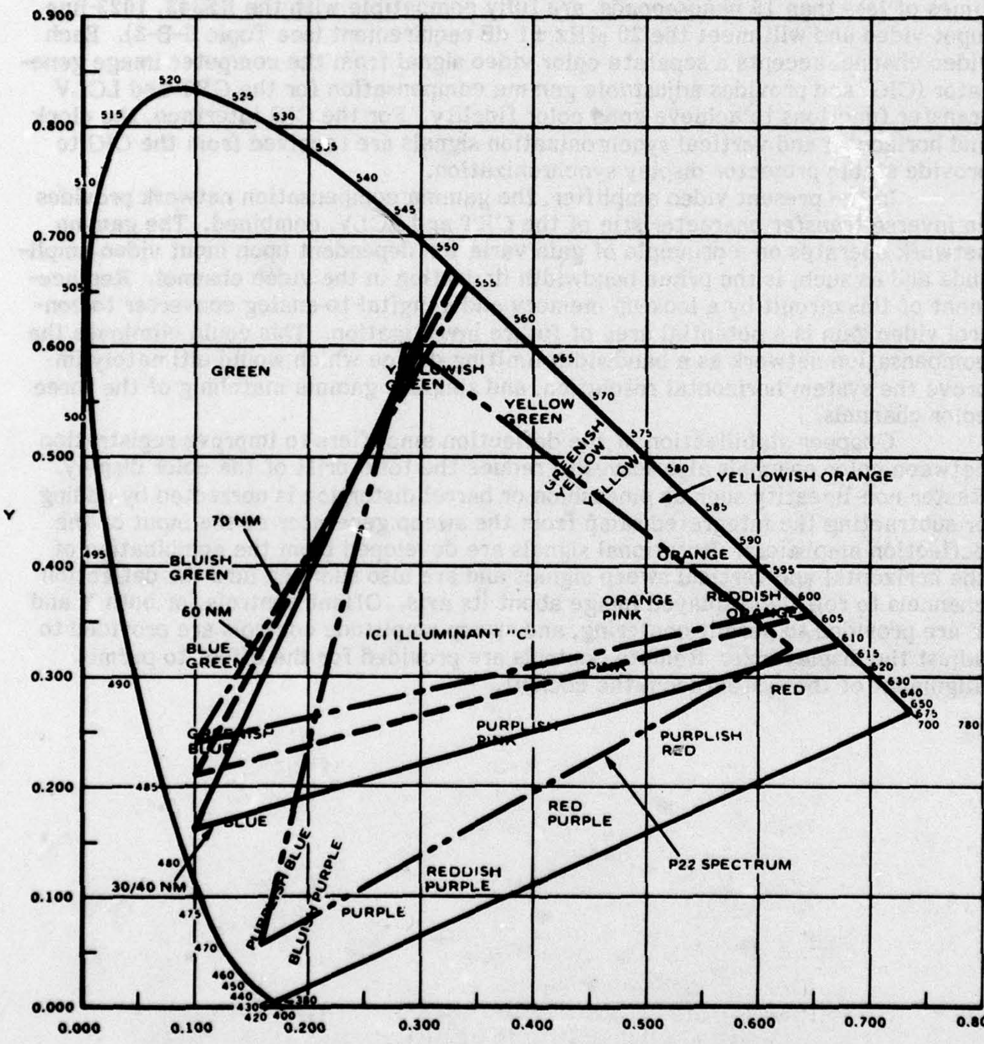


Figure 48. CIE Chromaticity Diagram. Color response of the LCLV Projector for 30/40 nm, 60 nm and 70 nm wide dichroic filters (at 50% points) are plotted. Plot of averaged P22 phosphor color response is shown for reference.

9. ELECTRICAL PERFORMANCE CHARACTERISTICS

Each of the three identical video channels is compatible with a 1000-TV-line input from a computer image generator. The raster generation circuitry utilizes a stable high gain analog sweep generator, digital and analog correction circuits, and chopper stabilization on the deflection amplifiers to provide a drift-free, stable projected image with minimal misregistration between color channels.

The degree of compliance of the recommended projector with the design requirements is tabulated in Table 25. The approach taken to meet each requirement is also briefly stated, and is elaborated in the text below.

The video amplifier channels, with a bandwidth of 30 MHz and rise and fall times of less than 15 nanoseconds, are fully compatible with the RS343, 1023-line input video and will meet the 20 MHz ±1 dB requirement (see Topic 6-B-3). Each video channel accepts a separate color video signal from the computer image generator (CIG) and provides adjustable gamma compensation for the CRT and LCLV transfer functions to achieve good color fidelity. For the CIG interface, the clock and horizontal and vertical synchronization signals are received from the CIG to provide stable projector display synchronization.

In the present video amplifier, the gamma compensation network provides an inverse transfer characteristic of the CRT and LCLV, combined. The gamma network operates on a principle of gain variation dependent upon input video amplitude and as such, is the prime bandwidth limitation in the video channel. Replacement of this circuit by a look-up memory and a digital-to-analog converter to control video gain is a potential area of future investigation. This could eliminate the compensation network as a bandwidth limiting device which would ultimately improve the system horizontal resolution, and simplify gamma matching of the three color channels.

Chopper stabilization of the deflection amplifiers to improve registration between color channels also serves to reduce the total drift of the color display. Raster non-linearity such as pincushion or barrel distortion is corrected by adding or subtracting the integrated ramp from the sweep generator at the input of the deflection amplifiers. Rotational signals are developed from the combination of the horizontal and vertical sweep signals and are also summed into the deflection channels to roll the displayed image about its axis. Offset controls for both X and Y are provided to permit centering, and sweep amplitude controls are provided to adjust the display size. Remote controls are provided for the offset to permit alignment of the system from the cockpit.

TABLE 25. ELECTRICAL PERFORMANCE OF LCLV PROJECTOR COMPARED TO SPECIFIED PARAMETERS

Electrical Parameter	Requirement	Projector Characteristics	Comment
Video Input	Simultaneous color per EIA STD RS 343,1023 lines at 1:1 aspect ratio	3 channels - additive color RS 343 compatible 985 active lines 38 retrace lines 1:1 aspect ratio	
Video Bandwidth	20 MHz ±1 dB $T_r = T_f = 25$ nsec overshoot <10%	20 MHz ±1 dB $T_r = T_f < 15$ nsec overshoot <10%	Bandwidth may be increased by further design effort or by digitizing the gamma compensation
Stability	Image drift < 0.5%	Image drift < ±0.1%	Minimized by use of separate deflection power supply and chopper stabilization
Alignment	Center, Size, Rotation	X and Y center for each channel X and Y gain for each channel Rotation adjustment for each channel	Center and size used to align to reference slide Rotation used to align adjacent projectors
Interface	CIG type image generator with fixed element rate output video	Differential line receiver on video line improves noise rejection	Normal design practices applied

10. EQUIPMENT CHARACTERISTICS OF PROJECTOR AND SUPPORT HARDWARE

Low weight and power, and shock/vibration integrity characterize the projector. Further weight reductions are possible at a slight increase of hardware cost.

This topic summarizes the equipment characteristics of the projector. The study addressed the mechanical configuration at the conceptual level – i.e., what is the approach to concurrently meeting acceleration, accessibility and alignability requirements without compromising the desirable goal of lowering weight. Consequently, the information presented here must be considered preliminary, and is likely to change (particularly at the system level) to tailor the projector to various system applications.

The size, weight and power dissipation figures for all discrete hardware elements of a multi-projector system using seven display channels are summarized in Table 26. The figures given for the projector are most meaningful; the central power supply weight is a rough estimate, as is the weight of the support structure. Detailed structural analysis is required to firm up the latter. Total on-platform system weight is approximately 2600 lbs. (see Table 26). Size/weight/power figures typical of currently available minicomputers and floppy discs are given for those two items.

Power dissipated by a complete multiprojector system of seven channels is estimated to be 32 kW. This is based on using a 1.6 kW lamp in the projector, and a lamp power supply efficiency of 60%. The total load on the air-conditioning system is approximately 24,000 BTU/hour.

The projector design is based on the concept of using a flat honeycomb baseplate panel as the mounting for all the optics, and to provide structural stiffening. By removing areas on the baseplate which are not contributing to either function, weight may be lowered significantly (by ~15%), which will lead to further reductions in system weight by cutting the weight of the structure supporting the projector.

The basic projector and the recommended structure for implementing a multiprojector system are expected to meet the shock/acceleration environment of the motion platform: roll, pitch and yaw of ±8, +10/−9, and ±16 radians/sec^2, respectively; and longitudinal lateral and vertical acceleration of +1.0/−1.35, ±1.0 and +4.3/−3.1 g's. All mechanical adjustments are pinned to ensure that they will not be dislodged under motion conditions.

The projector will operate over the temperature (60°F to 85°F) and humidity (10% to 60%) ranges expected to be encountered after installation.

TABLE 26. KEY PROJECTOR EQUIPMENT CHARACTERISTICS

	Size			Weight	Power
	H	W	D	(lbs.)	(watts)
Projector (each)	64"	38"	17"	280 (240[1])	3,100
Screens	15"	38"	-	30	0
Central Power Supply* (2 racks)	72"	38"	24"	1400**	8,800
Remote Panel (estimate)	16"	12"	4"	6**	30
Minicomputer*	8"	19"	16"	60**	1,000
Floppy Disc (dual drive)*	10"	19"	15"	20**	200
Cabling (80')		N/A		220	N/A
Structure		N/A		210	N/A
TOTAL ON PLATFORM[2]				2600 (2320)[1]	
TOTAL SYSTEM[2]				4086 lbs	31,730W

*Based on currently available typical hardware
**Off-platform electronics

(1) Alternate packaging configuration
(2) Based on assuming a seven projector system

11. RELIABILITY ESTIMATE OF THE PROJECTOR SYSTEM

Based on MIL-HDBK designated equipment failure rates, the MTBF of a single projector, excluding power supplies mounted off-platform, is approximately 8000 hours. The MTBF of a complete multiprojector system of seven channels with power supplies is 1130 hours.

Projector Reliability – To achieve a high degree of availability in a multiprojector system, the reliability of the individual projectors must be high. The recommended baseline concept achieves high reliability despite the fact that there are three complete CRT channels in each projector. This is attributable to the low power levels required in the video, deflection and high voltage circuits required to drive the CRTs as a result of the high deflection sensitivity CRT used. The low power levels result in fewer circuits, low voltage/power components which can be conservatively rated, and the centralization of the majority of the power supplies in a remote cabinet. These supplies can then be made redundant at low cost, without adding to the weight of the projector on the platform, and thus they contribute little to system failure rates.

The series-string model in Figure 49 shows a reliability block diagram for the projector. The projector MTBF (mean time between failures) is calculated for the failure rates (λ) given in the block diagram. The estimated failure rates are calculated for each system block based upon either similar components of previously manufactured equipments or the reliability handbook estimate for new components. The failure rates are based upon an ambient temperature of 25°C.

The expected life of the arc lamp is approximately 1500 hours, with the random failure rate estimated to be only 10 per 10^6 hours. The CRT and LCLV have an expected life of 5000 and 2000 hours, respectively, with the random failure rates again low – approximately 10 per 10^6 hours for the CRT and an estimated figure of 5 per 10^6 hours for the LCLV. As the lamp approaches end of life, light output begins to decrease. As the CRT and LCLV approach end of life, the contrast begins to decrease. The components, therefore, give an indication when approaching end of life. This can be used as a warning of impending failure and the component can be replaced during a period of non-use.

Under these conditions and assumptions, the single projector has an estimated MTBF of 8000 hours.

System-Level Reliability – Figure 50 depicts a reliability-oriented block diagram of the multiprojector system of seven channels. The central support equipment group is not considered part of the overall MTBF, since it is used for maintenance only. The central power supply group employs various degrees of redundancy to achieve reliability. Full redundancy of the low and medium voltage power supplies yields an essentially zero failure rate. By using eight lamp power supplies for the seven projectors (permitting the extra supply to be switched in to replace a failed supply), the arc lamp supply failure rate is reduced from 445 to 243. If a 1-day repair or replacement cycle is assumed for the failed supply, the failure rate is reduced by a factor of 20. The combined failure rate of the central power supply group is therefore 243/20 = 12.1, yielding an MTBF of 82,000 hours.

Based upon an MTBF of 8,000 hours for the basic projector and 82,000 hours for the power supplies, the complete projection system MTBF is calculated to be 1130 hours. Considering the complexity of the system, this is excellent reliability. Use of high reliability components in some of the high failure rate areas such as the high voltage power supplies and CRT bias circuits can further improve reliability with minimal hardware cost impact.

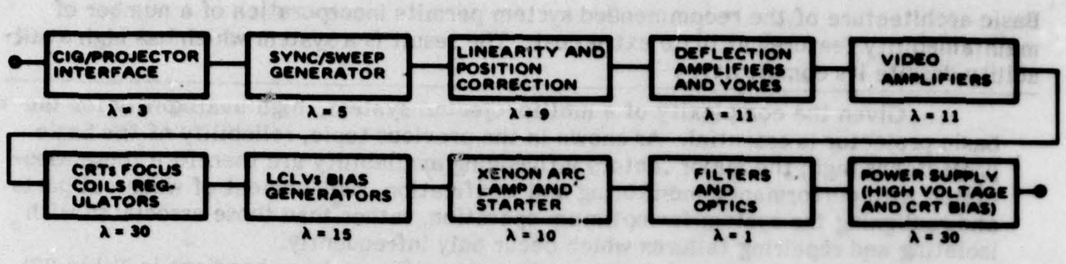


Figure 49. Reliability Diagram for the Single Projector. Since $\Sigma\lambda = 125$, the MTBF $= 10^6/\Sigma\lambda$ $= 8000$ hours.

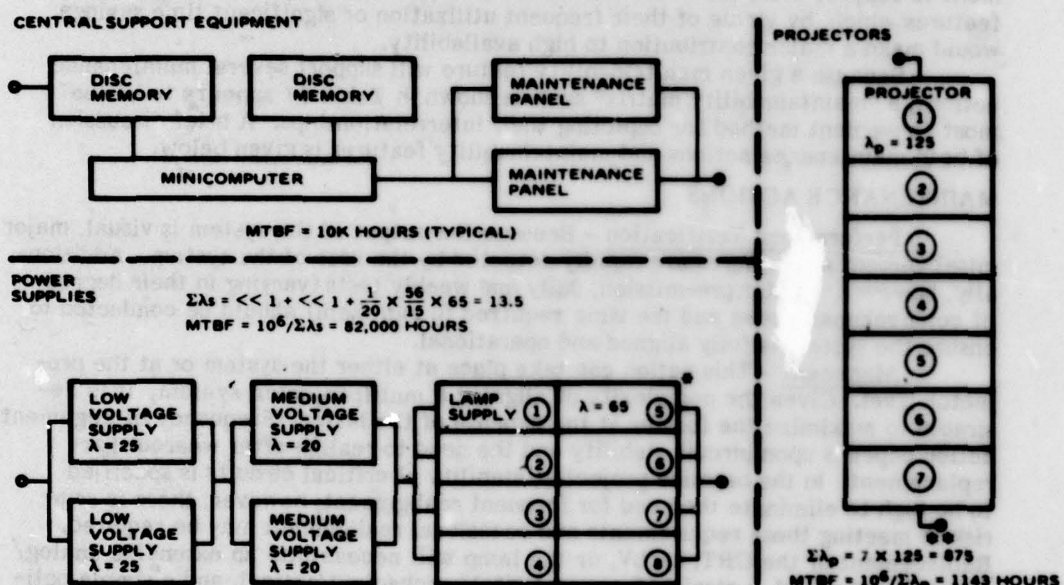


Figure 50. System Reliability Block Diagram. Since $\Sigma\lambda s = 13.5$ and $\Sigma\lambda_p = 875$, the system MTBF $= 10^6/\Sigma\lambda s + \Sigma\lambda_p = 10^6/(13.5 + 875) = 1130$ hours.

12. APPROACH TO ACHIEVING GOOD MAINTAINABILITY

Basic architecture of the recommended system permits incorporation of a number of maintainability features at little extra cost. The result is a system which has high availability despite its complexity.

Given the complexity of a multiprojector system, high availability for the basic projector is essential. As shown in the previous topic, reliability of the basic projector is high; the major factors influencing availability are therefore those associated with performance monitoring and verification, replacement of wear-out parts and realigning the system for optimum operation, rather than those associated with isolating and repairing failures which occur only infrequently.

Given the variety of maintenance actions (see column headings in Table 27) and the variety of features which can be implemented, the scope of the study did not permit the detailed and comprehensive analysis that this area deserves in view of its importance. Rather, an attempt was made to identify both the possible maintenance actions, and the maintainability features which should be provided in the equipment to support those maintenance actions. Emphasis was placed on maintainability features which, by virtue of their frequent utilization or significant time savings, would make a major contribution to high availability.

Because a given maintainability feature will support several maintenance actions, a "maintainability matrix" such as shown in Table 27 appears to be the most convenient method for depicting their interrelationships. A brief discussion of both maintenance actions and maintainability features is given below.

MAINTENANCE ACTIONS

Performance Verification – Because the output of the system is visual, major misalignment and failures are rapidly detected by the user of the system. Additionally, however, regular pre-mission, daily and weekly tests (varying in their degree of comprehensiveness and the time required to run them) should be conducted to ensure the system is fully aligned and operational.

Alignment – This action can take place at either the system or at the projector level. Given the complexity of aligning a multiprojector system, it is desirable to maximize the former at the expense of the latter. Frequency of alignment action depends upon circuit stability and the need to realign after wearout part replacement. In the baseline projector, stability of critical circuits is specified to be high to eliminate the need for frequent realignment; however, there is some risk in meeting these requirements and occasional realignment may be required. Replacement of the CRT, LCLV, or the lamp will necessitate an extensive analog/digital/mechanical, a straightforward digital/mechanical/optical, and a simple optical alignment, respectively, (all of these are at the projector level). System realignment should be required only in case of replacing a full projector, a projection lens, or a screen on a pancake window – all of which are expected to be infrequent occurrences. (System alignment procedure is described in Topic 7-7.)

Replacement of Wearout Parts – As mentioned the CRT, the LCLV and the xenon lamp are the primary wearout parts in the system (see topic on reliability for average life of these components). Their replacement requires ease of access, mechanical alignment devices which securely lock, and test patterns to assist realigning after part replacement.

Fault Isolation – The ability to directly observe the display is a powerful diagnostic/fault isolation tool. In the baseline system, an estimated 70 percent of the faults can be tentatively isolated down to a couple of cards or assemblies. Where this is not possible, the straightforward nature of the signal flow, coupled

with the ability to compare to one of the other two channels permits a logical and rapid isolation of faults down to a single card/assembly in an estimated 95 percent of the cases.

Fault Repair – The great majority of the failures will be electronic cards which are housed in a card box, and can be replaced in less than a minute once accessed. Other electronic assemblies (power supplies, deflection amplifiers) require mechanical dismounting and replacement, and therefore require somewhat more time than card replacement. Replacement of optical components – which should occur very infrequently – could be a lengthy affair, requiring careful realignment of the system after replacement. Length of time to repair is component-dependent.

Routine Maintenance – At monthly intervals the optical components in the system should be inspected for accumulation of dirt and dust, and cleaned if necessary.

TABLE 27. MAINTAINABILITY FEATURES TO SUPPORT REQUIRED MAINTENANCE ACTIONS

Class	Maintainability Features	Performance Verification	System Alignment	Projector Alignment	Replacement of Re-work/Wearout Parts	Fault Isolation	Fault Repair	Routine Maintenance
Mainte-nance Specific	Test pattern selection	(X)	-	(X)	X	(X)	-	-
	Reference slide	X	(X)	(X)	-	-	-	-
	Computer aided alignment	-	-	(X)	-	-	-	-
Equipment	Ease of Access to							
	Wearout parts	-	-	-	(X)	-	-	-
	Adjustments	-	X	(X)	X	-	X	-
	Test points	-	-	X	-	(X)	X	-
	Card replacement	-	-	(X)	(X)	-	(X)	-
	Ease of securing optical/ mechanical adjustments	-	X	X	(X)	-	X	-
	Dust protection	-	-	-	-	-	-	(X)
Elec-tronics	Stable deflection circuits	X	X	(X)	-	-	-	-
	Simple signal flow	-	-	-	-	(X)	-	-
	Three identical channels	-	-	-	-	X	X	-

X – Interaction/impact
(X) – Major interaction/impact

Preceding Page Blank - NOT FILMED

12. APPROACH TO ACHIEVING GOOD MAINTAINABILITY (Continued)

MAINTAINABILITY FEATURES

To support the preceding maintenance actions, the feasibility of incorporating a variety of widely different maintainability features was considered for both the basic projector and the overall system. The features described below are ones which can be implemented at little extra cost to the system if they are incorporated into the design concept at its inception. All of the features described have been incorporated in the baseline system. It was gratifying to find in the study that excellent maintainability should be achievable without appreciable impact on cost.

As shown in Table 27, most maintainability features support (or contribute to) more than one maintenance action. The degree of impact is signified in the table.

Test Pattern Selection – The capability to display a variety of test patterns is provided to support performance verification, projector alignment and fault isolation. Typical patterns include a crosshatch (distortion), full raster (color registration), resolution, shades of gray, color test, uniformity, etc., and include patterns that may be designed to assist signal monitoring of test points for troubleshooting. Digital logic to generate these test patterns is incorporated into each projector; local generation eliminates degradation of the video (and hence visual quality) due to video line drivers and cabling. In addition, a 1M bit test pattern memory is provided to store special test patterns which are stored on disc, and are called up by the operator via the computer. Because of memory limitations, these test patterns may have to consist of repeated subpatterns.

Reference Slide – A reference slide incorporated in each projector is a key element in maintaining overall system alignment (i.e., minimizing interwindow discontinuity) yet permits each projector to be aligned independently. This feature is described in detail in Topic 7-7.

Computer Aided Alignment – Complete manual entry of values for the 1024-point correction memory (to achieve good color registration) for each of three channels of seven projectors (21,504 points!) is totally impractical. Computer algorithms to aid the operator to rapidly recalculate correction values based on the entry of a few points will be used to reduce this task by a couple of orders of magnitude. Simple entries will compensate for effects of drift (in gain or offset), rotation, or size change.

Ease of Access – Means of easily accessing wearout parts for replacement, electrical adjustments for projector alignment, test points for fault isolation and alignment, and removable cards/assemblies for replacement in event of failure are designed into the system.

Securing of Mechanical Adjustments – Once mechanical or optical adjustment is made, it must be secured to avoid slipping/shifting with platform motion. This will minimize the need to continually realign/readjust the system. Covers to protect all optical components and the screen from dust and dirt are provided. Covers will be easily removable for inspection and replacement of wearout parts.

Stable Deflection Circuits – This feature is a key element in keeping the system alignment-free; excessive drift implies continued realigning of the system to maintain good color registration. Both gain and offset of the deflection system (the major contributor to drift) are critical. Chopper stabilization and gain stabilization are provided to hold total drift to below 0.03 percent.

Simple Signal Flow – The inherent simplicity of signal flow through the system greatly simplifies fault isolation, and reduces skill level required for maintenance.

Three Identical Channels – The three channels being identical aids troubleshooting by allowing channel-to-channel comparison and interchanging of cards to isolate malfunctioning units.

13. ALTERNATE DISPLAY CONFIGURATIONS

The projection optics required to accommodate alternative display configurations are very similar to the baseline projection optics except for the small projection-angle flat-screen case.

The RFP for this study required that the following alternatives to the baseline configuration (which generates a pentagonal display on a 24" radius curved screen) be considered: 1) a rectangular (either 1:1 or 4:3 aspect ratio) display on a curved screen; and 2) a rectangular (1:1 or 4:3) display on a flat screen. A more detailed description/definition of these requirements is given in Section 2, p 23. Note that the size of, and distance to, the flat screen were not specified.

These configurations are examined below based on the assumption that the vertical dimension always contains approximately 1000 raster lines. This implies that for the 4:3 aspect ratio rectangular display the number of horizontal display elements will be 4/3 x 1000 = 1333. All resolution figures in Table 28 were calculated based on this assumption.

The following points should be considered in examining the various configurations:

1. Regardless of the shape of the projected image, the available 1.8" diameter area of the LCLV should be fully utilized to maximize resolution of the displayed image. Note that to allow for adjustments/alignment of the display, a tolerance of 0.1 inch is provided. It follows that the projection optics just provide for coverage of a 1.7 inch diameter object for all the configurations considered.
2. The vertical and horizontal resolutions obtainable for different display configurations (shapes) should be calculated based on the displayed image shape inscribed in the 1.7 inch diameter circle. Figure 51 shows a pentagon, a square and a 4:3 rectangle inscribed in this circle. Relative raster widths are 0.95 D, 0.71 D and 0.80 D, respectively; and relative raster heights are 0.91 D, 0.71 D and 0.60 D respectively (D is diameter of LCLV circular usable area).
3. The projection optics for a 24 inch radius screen is not affected by the image shape inscribed in the circle, and will be identical to that proposed for the baseline projector. For the flat screen cases, the projection optics will require a different projection lens – basically a conventional f-tan θ mapping type – and the relay system may not be required if the throw distance magnifications are such that the ratio of back focal length (BFL) to the effective focal length (EFL) is considerably less than 2.0; i.e., if the projection angle is considerably less than 35°.

Table 28 summarizes the impact of the various curved screen/flat screen and pentagonal/rectangular combinations on the size of the inscribed raster, the horizontal and vertical resolution, the projection optics mapping requirements and whether a relay system is required to implement the projection optics. All of the display configurations considered are feasible. To select the "best" projection optics for each case would require setting up criteria for optimization and performing trade-off studies similar to the one conducted for the baseline system. Since this was not within the scope of this study, the resolution characteristics of the baseline system projection optics (see Figure 51) were used to calculate horizontal and vertical resolution figures.

As seen in Table 28, the baseline system has the highest resolution. This is attributable to its effective use of the available area on the light valve.

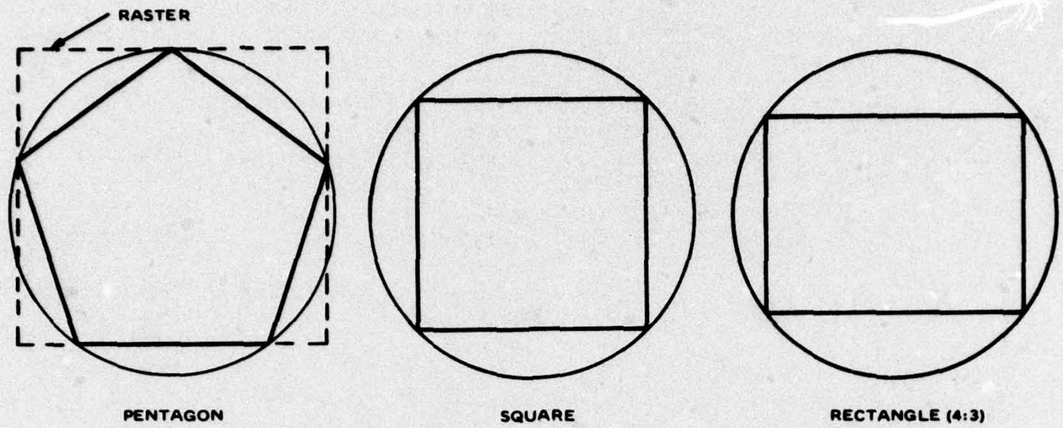


Figure 51. Comparison of Pentagonal, Square and 4:3 Rectangular Display Configurations. For the rectangular formats the raster coincides with the displayed area.

TABLE 28. IMPACT OF DISPLAY CONFIGURATION ON RESOLUTION AND PROJECTION OPTICS

Configuration		Raster Size		Resolution(1)		Projection Optics	
Screen Type	Shape/ Aspect Ratio	Horiz.	Vert.	Horiz.	Vert.	Mapping	Relay ?
Curved(2)	Pentagonal	0.95D	0.91D	30%	33	Baseline(3)	Yes
Curved(2)	Square/1:1	0.71D	0.71D	14	18	Baseline	Yes
Curved(2)	Rectangle/ 4:3	0.80D	0.60D	21	10	Baseline	Yes
Flat	Square/1:1	0.71D	0.71D	14	18	f-tan θ	Note 4
Flat	Rectangle/ 4:3	0.80D	0.60D	21	10	f-tan θ	Note 4

(1) Resolution expressed as MTF at 1000 lines
(2) Curvature of screen is 24 inches; projection optics for all three cases are identical
(3) See P. 23 for definition of required mapping
(4) If projection angle is < 35°, a relay system may not be required, otherwise, optics are same for both

Preceding Page Blank - NOT FILMED

REFERENCE

Beardsley, H., Bunker, W., Eibeck. A., Juhlin, J., Kelly, W., Page, J., & Shaffer, L. Advanced simulation in undergraduate pilot training: computer image generation. AFHRL-TR-75-59(V), AD-A022 251. Wright-Patterson AFB, OH: Advanced Systems Division, Air Force Human Resources Laboratory, November 1975.

★ U.S. GOVERNMENT PRINTING OFFICE: 1977—771-122/80